LLNL-PROP-406918

Advanced Target Design for Fast Ignition

Principal Investigator: Max Tabak
AX-Division
Lawrence Livermore National Laboratory

Lawrence Livermore National Laboratory
PO Box 808, L-472
Livermore, CA 94550

p: 925-423-4791
f: 925-422-9690
Tabak1@llnl.gov

A Proposal Submitted to
The OFES-NNSA Joint Program
High Energy Density Laboratory Plasmas
DOE National Laboratories
LAB 08-16

September 11, 2008

Additional "cover" information is provided on the Field Work Proposal (DOE 412.1A) and budget (DOE 4620.1) forms that follow.

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U.S. DEPARTMENT OF ENERGY FIELD WORK PROPOSAL - FY 2010*

1. Work Proposal Number	2. Revision Number	3. Date Prepared	3a. Approved
SCW0873	0	09/08/08	Y

4. Work Proposal Title	5. Budget & Reporting Code
Advanced Target Design for Fast Ignition	AT5015033

6. Work Proposal Term	7. Is this work package included in the Institutional Plan?
Begin: 10/01/08 End: 09/30/11	Y

Name (Last, First, MI) (Phone Number)		
8. Headquarters Program Manager JOHN SAUTER 301-903-3287	11. Headquarters Organization SC24.2 - Research Divisi	14. DOE Code SC24.2
9. Operations Office Work Proposal Reviewer SCOTT, RICHARD	12. Operations Office Livermore Site Office	15. DOE Code LSO
10. Contractor Work Proposal Manager GOLDSTEIN, WILLIAM H 925-422-2515	13. Contractor Name LLNS/LLNL	16. DOE Code 50

17. ABSTRACT:

This proposal constitutes a broad range of work to advance target design for fast ignition applications leading to practical production of fusion energy. Topics to be addressed include: 1) Mitigation of deleterious prepulse effects in conventional laser systems such as NIF using micro- and nano-particles in the target; 2) Direct drive fast ignition targets that can be imploded with two beams to allow thick liquid wall protection in the chamber; 3) Targets without cones designed to minimize plasma distance through with laser produced electrons must propagate; 4) Use integrated modeling tools to develop high-Z tamped fuel targets to reduce ignition energy and 5) Study relativistic beam-plasma instabilities analytically and with simulations to identify parameter ranges where beam control is an issue and to support benchmarking of simulation tools necessary for design verifications. This proposal complements ongoing efforts to field integrated experiments at Omega EP and the NIF/ARC facility.

18. CONTRACTOR WORK PROPOSAL MANAGER		19. OPERATIONS OFFICE WORK PROPOSAL REVIEWER	
W. B. Baner	9/8/08	Richard A. Scott	9/9/08
(Signature)	(Date)	(Signature)	(Date)
GOLDSTEIN, WILLIAM H		SCOTT, RICHARD	

20. DETAIL ATTACHMENTS: (See Attachments)

__a. Facility Requirements	x b. Publications	x c. Purpose
x d. Background	x e. Approach	__f. Technical Progress
__g. Future Accomplishments	__h. Rltnshp to Other Proj	__i. NEPA Requirements
x j. Milestones	x k. Deliverables	x l. Perf. measures/expect.
__m. ES&H Considerations	__n. Human/Animal Studies	__o. Other (Specify)

Note: Rates used for proposal pricing are based upon the assumption that LLNL will fully implement the NNSA-approved 3161 workforce restructuring plan. Rates also assume significant reductions to non-labor cost elements of the indirect budgets. Rates are subject to change due to changes in program funding levels, compliance requirements and cost accounting practices.

WORK PROPOSAL REQUIREMENTS FOR OPERATING/CAPITAL EQUIPMENT

OBLIGATIONS AND COSTS

Work Proposal Number	B&R Code	Contractor Name	Rev.No.	Date Prepared
SCW0873	AT5015033	LLNS/LLNL	0	09/08/08

	PRIOR YEARS	BY-2 FY 08	BY-1 GUIDANCE FY 09	BY-1 REQUEST FY 09	BY GUIDANCE FY 10	BY REQUEST FY 10	BY +1 GUIDANCE FY 11	BY +2 + TOTAL TO COMPLETE
21. LLNL STAFFING (LLNL FTEs)								
a. SCIENTIFIC	0.0	0.0	1.5	1.5	1.4	1.4	1.4	0.0
b. OTHER DIRECT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
c. TOTAL DIRECT	0.0	0.0	1.5	1.5	1.4	1.4	1.4	0.0
22. OPERATING (in thousands)								
a. OBS. (BA)	0	0	500	500	500	500	500	0
b. COSTS (BO)	0	0	500	500	500	500	500	0
23. CAP. EQUIP. (in thousands)								
a. OBS. (BA)	0	0	0	0	0	0	0	0
b. COSTS (BO)	0	0	0	0	0	0	0	0
22+23. TOTAL($K)								
a. OBS. (BA)	0	0	500	500	500	500	500	0
b. COSTS (BO)	0	0	500	500	500	500	500	0

24. MILESTONE SCHEDULE (tasks)	BY ($K) GUIDANCE	BY ($K) REQUEST	SCHEDULE GUIDANCE	SCHEDULE REQUEST
per HQ Requirements				09/30/11

25. PROJECT OBJECTIVE (DESCRIPTION)/REMARKS 32. CRADA Project (Y/N)?

Implosion Design:

Design 1-D implosions with high-Z tampers with multiple shock pulseshape as well as pulseshape leading to self-similar isochoric fuel configurations in direct and indirect drive culminating in a full integrated design; Develop prepulse mitigation scheme; Implosion design without a cone leading to short critical surface distance to high fuel density; and Design directly driven implosion from opposite poles.

Electron beam-plasma instabilities:

Carry out parametric Vlasov simulations to characterize most important instabilities, finite beam effects, saturation effects, and beam collimation; Analyze acoustic and drift instabilities for relevant parametric constraints; and Develop reduced saturation models and characterize collision induced effects.

33. PRINCIPAL INVESTIGATORS

TABAK, MAX 925-423-4791

DOE F 4620.1

(04-93)

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U. S. Department of Energy

Budget Page

(See reverse for Instructions)

OMB Control No.

1910-1400

OMB Burden Disclosure

Statement on Reverse

ORGANIZATION LAWRENCE LIVERMORE NATIONAL LABORATORY				**Budget Page No:** YEAR 1	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR MAX TABAK				Requested Duration: 12 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Amount in Whole Dollars Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. MAX TABAK - PRINCIPAL INVESTIGATOR	1.4			18,894	
2. STEVEN LUND - CO INVESTIGATOR	4.8			50,673	
3. DMITRI RYUTOV - CO INVESTIGATOR	1.2			15,745	
4. SCOTT WILKS - CO INVESTIGATOR	1.2			12,668	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (4) TOTAL SENIOR PERSONNEL (1-6)	8.6			97,980	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	9.0			52,178	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				150,158	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				78,348	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				228,506	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				12,000	
2. FOREIGN					
TOTAL TRAVEL				12,000	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				4,000	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				4,000	
H. TOTAL DIRECT COSTS (A THROUGH G)				244,506	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				255,380	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				499,886	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				499,886	

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ORGANIZATION LAWRENCE LIVERMORE NATIONAL LABORATORY				**Budget Page No:** YEAR 2	
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR MAX TABAK				Requested Duration: 12 (Months)	
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Amounts in Whole Dollars Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. MAX TABAK - PRINCIPAL INVESTIGATOR	1.4			19,555	
2. STEVEN LUND - CO INVESTIGATOR	4.3			47,333	
3. DMITRI RYUTOV - CO INVESTIGATOR	1.2			16,296	
4. SCOTT WILKS - CO INVESTIGATOR	1.2			13,112	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (4) TOTAL SENIOR PERSONNEL (1-6)	8.10			96,296	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	9.0			54,004	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				150,300	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				78,227	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				228,527	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				12,240	
2. FOREIGN					
TOTAL TRAVEL				12,240	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				4,080	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				4,080	
H. TOTAL DIRECT COSTS (A THROUGH G)				244,847	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				255,160	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				500,007	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				500,007	

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ORGANIZATION				**Budget Page No:**	YEAR 3
LAWRENCE LIVERMORE NATIONAL LABORATORY					
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR				Requested Duration:	12 (Months)
MAX TABAK					

A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos. CAL	ACAD	SUMR	Amounts in Whole Dollars Funds Requested by Applicant	Funds Granted by DOE
1. MAX TABAK - PRINCIPAL INVESTIGATOR	1.4			20,239	
2. STEVEN LUND - CO INVESTIGATOR	3.8			43,887	
3. DMITRI RYUTOV - CO INVESTIGATOR	1.2			16,866	
4. SCOTT WILKS - CO INVESTIGATOR	1.2			13,570	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (4) TOTAL SENIOR PERSONNEL (1-6)	7.60			94,562	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES				55,895	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				150,457	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				78,109	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				228,566	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				12,480	
2. FOREIGN					
TOTAL TRAVEL				12,480	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				4,166	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				4,166	
H. TOTAL DIRECT COSTS (A THROUGH G)				245,212	
I. INDIRECT COSTS (SPECIFY RATE AND BASE)					
TOTAL INDIRECT COSTS				254,950	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				500,162	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				500,162	

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Budget Page

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OMB Control No.
1910-1400
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Statement on Reverse

ORGANIZATION LAWRENCE LIVERMORE NATIONAL LABORATORY				**Budget Page No:**	YRS 1 - 3
PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR MAX TABAK				Requested Duration:	36 (Months)
A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets)	DOE Funded Person-mos.			Dollars Funds Requested by Applicant	Funds Granted by DOE
	CAL	ACAD	SUMR		
1. MAX TABAK - PRINCIPAL INVESTIGATOR	4.2			58,688	
2. STEVEN LUND - CO INVESTIGATOR	12.9			141,893	
3. DMITRI RYUTOV - CO INVESTIGATOR	3.6			48,907	
4. SCOTT WILKS - CO INVESTIGATOR	3.6			39,350	
5.					
6. ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE)					
7. (4) TOTAL SENIOR PERSONNEL (1-6)	24.3			288,838	
B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)					
1. (1) POST DOCTORAL ASSOCIATES	18.0			162,077	
2. ( ) OTHER PROFESSIONAL (TECHNICIAN, PROGRAMMER, ETC.)					
3. ( ) GRADUATE STUDENTS					
4. ( ) UNDERGRADUATE STUDENTS					
5. ( ) SECRETARIAL - CLERICAL					
6. ( ) OTHER					
TOTAL SALARIES AND WAGES (A+B)				450,915	
C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS)				234,684	
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C)				685,599	
D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM.)					
TOTAL PERMANENT EQUIPMENT					
E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				36,720	
2. FOREIGN					
TOTAL TRAVEL				36,720	
F. TRAINEE/PARTICIPANT COSTS					
1. STIPENDS (Itemize levels, types + totals on budget justification page)					
2. TUITION & FEES					
3. TRAINEE TRAVEL					
4. OTHER (fully explain on justification page)					
TOTAL PARTICIPANTS ( ) TOTAL COST					
G. OTHER DIRECT COSTS					
1. MATERIALS AND SUPPLIES					
2. PUBLICATION COSTS/DOCUMENTATION/DISSEMINATION				12,246	
3. CONSULTANT SERVICES					
4. COMPUTER (ADPE) SERVICES					
5. SUBCONTRACTS					
6. OTHER					
TOTAL OTHER DIRECT COSTS				12,246	
H. TOTAL DIRECT COSTS (A THROUGH G)				734,565	
I. INDIRECT COSTS (SPECIFY RATE AND BASE) See 'Attachment A'					
TOTAL INDIRECT COSTS				765,490	
J. TOTAL DIRECT AND INDIRECT COSTS (H+I)				1,500,055	
K. AMOUNT OF ANY REQUIRED COST SHARING FROM NON-FEDERAL SOURCES					
L. TOTAL COST OF PROJECT (J+K)				1,500,055	

Attachment A

Lawrence Livermore National Laboratory
Estimated FY2009 Rates - subject to change with DOE approval

Program Management Charge (PMC):	6.70%	Rate established for costs associated with managing and administering programs within a Directorate. This includes management, administration, program development, clerical support, services and technical support and other indirect functions in support of direct programmatic activities. Charged to a PMC value added base consisting of total costs less procurements, subcontracts and travel.
General & Administrative (G&A):	26.00%	Rate established to recover the costs associated with general and administrative management of the Laboratory as a whole. Charged to a value added base consisting of total costs less procurements, subcontracts and travel.
Strategic Mission Support (SMS):	8.90%	Rate pays for science and technology strategic planning, outreach, special employees, and institutional capabilites and other activities that enhance the Laboratory's ability to address future missions. Charged to a value added base consisting of total costs less procurements, subcontracts and travel.
Site Support	39.10%	Rate used to distribute the costs for the management, maintenance and upgrades of the general purpose facilities and property, and for the provision of basic infrastructure services and safety across the Laboratory. Charged to a value added base consisting of total costs less procurements, subcontracts and travel.
Laboratory Directed Research & Development (LDRD):	8.70%	Rate covers the cost of projects that enhance scientific and technological vitality of the Laboratory. Charged to a value added base consisting of total costs.
Management Fee:	10.30%	Management fee is established under Prime Contract No. DE-AC52-07NA27344 for management of Lawrence Livermore National Laboratory (LLNL) by Lawrence Livermore National Security, LLC (LLNS). Charged to a value added base consisting of total costs less procurements, subcontracts and travel.

1. Executive Summary

Advanced Target Design for Fast Ignition

Participants:
PI: Max Tabak, LLNL
Steven M. Lund, LLNL
Dimitri Ryutov, LLNL
Scott Wilks, LLNL

Principal Investigator (PI) Contract Info:
Lawrence Livermore National Laboratory
PO Box 808, L-472
Livermore, CA 94550

(925) 423-4791
Tabak1@llnl.gov

Fast Ignition has emerged as a serious alternative to central hotspot ignition as an approach to achieving inertial fusion in the laboratory. Fast Ignition supports both defense and civilian applications. For NNSA and astrophysical applications (in response to charge 1), Fast Ignition is another route to ignition in the laboratory as well as a source of extremely high energy density. In response to all aspects of charge 2, the primary civilian application is fusion energy: Fast Ignition can lead to gains several times higher than conventional central hotspot ignition and hence produce adequate gains for much lower total driver scale and cost. This proposal addresses several issues which will affect near term tests of Fast Ignition as well as ways to improve its reactor realizations. This proposal complements a number of ongoing efforts to field integrated experiments at Omega EP and the NIF/ARC facility.

1. Radiation hydrodynamic calculations and experiments have shown that even low levels of ASE prepulse (~10 mJ) in the short pulse laser can produce hundreds of microns of underdense plasma in the cone used in the cone-in-shell technique that is now the leading approach to Fast Ignition. Recent PIC calculations and experiments suggest that the interaction of this plasma with the incident laser beam efficiently produces relativistic electrons that are then driven into the cone wall rather than towards the fuel. The solution will likely involve reducing this prepulse. There exist technologies that can reduce this prepulse by many orders of magnitude, but they may be difficult and expensive to implement at near term facilities like the advanced radiographic capability (ARC) under construction at the NIF. We intend to design a medium composed of micro- and nano-particles that will absorb the prepulse, but disperse before the main pulse arrives to mitigate this problem consistent with existing short pulse laser systems.
2. Reactors will be easier to design if the number of holes in the reaction chamber is minimized. We want to design Fast Ignition targets that can be imploded by direct drive coming from a small solid angle in just two beams, thereby allowing the use of thick liquid wall protected chambers.
3. Fabricating targets with attached cones is difficult. We want to design implosions that minimize the plasma through which the short pulse laser must propagate, obviating the cone requirement.
4. Tamping fuel with high-Z overcoating reduces the ignition energy. Simple 1-D burn calculations have shown at least 1 kJ of thermonuclear yield when the fuel is heated with 1 kJ. We want to design implosions integrating our hydro codes, electron transport codes, and explicit PIC codes that can achieve this idealized behavior. Integrated modeling promises to enable reliable development of this target concept which may provide the earliest route to Fast Ignition demonstration.
5. Electron beam-plasma instabilities may produce enhanced stopping and scattering of the relativistic electron beam produced in the laser-plasma interaction. Controlling instabilities may constrain the allowed background plasma parameters. These instabilities will be studied analytically and with 3D PIC codes to better understand parametric constraints and to support benchmarking of simulation tools used to verify design concepts.

2. Background, Progress, and Current Status

2.1 Background

2.1.1 Physics issues

The physical outlines of fast ignition (FI) fusion have been known for at least 10 years [Bas92, Tab94, Tab97], and the basic requirements are well known [Atz99, Ros99]. FI differs from the conventional central-hot-spot (CHS) approach in using separate drivers for the compression and ignition steps illustrated in Fig. 1. This eliminates the need for a shock-heated, low-density ignition spot surrounded by a dense core (see Fig. 1a), allows compression of the target to a uniform density (~1/3), and uses a smaller mass ignition region (~1/10) than that of the CHS approach (see Fig. 1b). The consequent reduced energy input results in a very attractive improvement in target gain (Fig. 2). A comprehensive gain model [Tab04, Tab05] that includes ignition requirements, hydrodynamic efficiency and assembly effects as well as the coupling efficiency from the ignition driver to the fuel, highlights the sensitivity of the ultimate FI gain to various system parameters. Table 1 shows the effects of reducing the energy required for ignition, reducing the coupling of the ignition driver, reducing the hydrodynamic efficiency, increasing the range of the particles that heat the fuel to ignition temperature, and changing the wavelength of the compression laser from blue to green for capsules compressed directly with laser light. These parameters enable more attractive power plant designs than those based on a conventional CHS target.

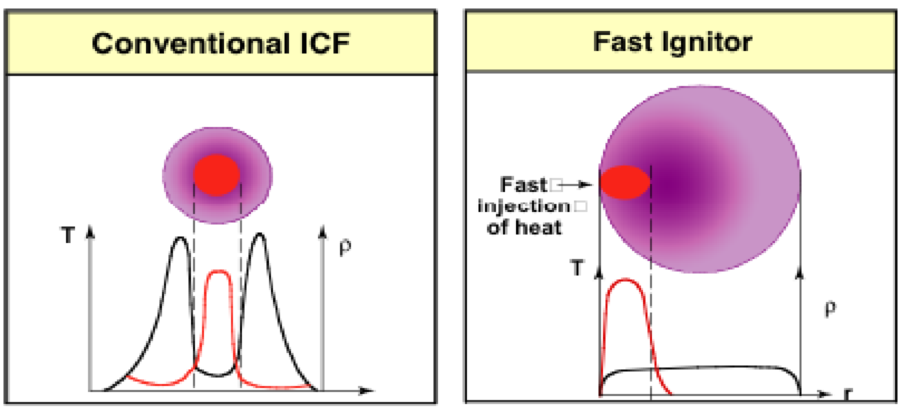

Figure 1: Density and temperature profiles at stagnation of a) a conventional central hot spot ICF target and b) a fast ignition target.

The ignition driver in FI is an ultra-high-intensity (UHI) laser that delivers the energy to initiate the fusion burn. In the initial concept [Tab94], an UHI laser bores through the lower-density plasma surrounding the assembled target to the relativistic critical density surface and then steepens the plasma density profile pushing the critical density surface toward the dense fuel. At the critical surface, the laser energy is converted into relativistic electrons that deposit their energy in the dense (~300 g cm^{-3}) core of the target. The required areal density of the ignition spot (~0.3-1.2 g cm^{-2}) determines the required electron energy (1 to 2 MeV) and, through the relationship between the average electron energy and the laser intensity [Beg97], the intensity of the required FI laser (~10^{20} W cm^{-2} μm^{-2}) is derived. Later work [Wha98, Pis00, Yas01] showed that at this intensity >30% of the laser energy is converted into electrons.

The relativistic electrons need to traverse a density increase from 3×10^{-3} g cm^{-3} to 300 g cm^{-3} before depositing their energy in a ~40-μm-diameter spot in the compressed core (which is ~300 μm in diameter). Collimation of the electrons transported is a critical issue. Consequently, the distance over which the transport occurs is therefore envisaged as not exceeding about 100 µm. The previously mentioned channeling is one possibility to accomplish this. Alternative target designs may also limit transport distance. An important development was a variant target design containing a reentrant cone [Tab97, Hat01] that allowed electron generation closer than 100 µm from the core.

Parameter	E_{total}(MJ)
Nominal model	0.3
E_{ign} x 1/2	0.1
η_{ign} x 0.25	1.7
η_{hydro} x 0.5	0.95
$range_{ign}$ x 3	0.75
0.5 µm drive	0.55

Table 1: Driver energy at which gain 100 is reached under a number of model assumptions.

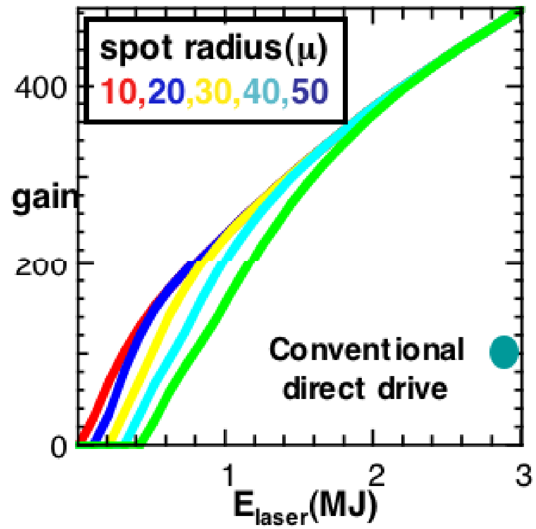

Figure 2: Expected target gain versus driver energy for fast ignition for various spot radii compared to a conventional direct drive point.

The first integrated FI experiments at about 1% of full-scale energies used this cone design and demonstrated ~25% efficient coupling of short-pulse laser energy to an implosion core, giving an important boost to confidence in fast ignition [Kod02]. These results exceeded naive expectations. Only about 20% of the energy delivered by the Osaka petawatt laser, where these experiments were performed, was focused to a central maximum comparable to the compressed capsule size. Ponderomotive scaling of electron particle energy with laser intensity [Wil92] predicts that most of the electrons produced in the laser-plasma interaction had ranges long compared to the capsule size (2-3 times longer). If 30% laser-relativistic electron coupling efficiency is inferred from earlier experiments and one assumes good collimation from the laser spot to the capsule, we might expect 2-3% coupling efficiency to the compressed core. The much higher measured coupling efficiency indicates that there may be several unexpected effects that can enhance coupling. More recent simulations [Chr08] where laser light is injected down a cone with a very short (~10 micron) preformed plasma into a spot size comparable to the compressed capsule, show 30% coupling into much less energetic electrons and an additional 50% into electrons with a ponderomotive spectrum. With ~100% transport efficiency to the dense fuel core, this laser-electron coupling can explain the Osaka data. However, there may be disruptions in electron transport due to beam-plasma instabilities as well as a divergence of the initial electron beam produced in the laser-plasma interaction. Limitations of the transport due to beam-plasma instabilities is one subject of this proposal. Understanding such transport limitations is essential to designing reliable targets. Furthermore, it is unlikely that preformed plasma at the tip of the cone was as small as 10 microns when the high intensity laser beam was launched (see discussion below). It has also been suggested that the cones may focus incident light and/or transport the generated electrons along the surface of the cone to its apex and the ignition region.

Channeling light down cones with decreasing opening angles for laser beams nominally focused at f/7 to a 50 micron rms radius focal spot lead to increasing fractions of energy coupled to the cone in a 10 micron radius. In existing experiments the laser spot is composed of 20-30% of the light in a spot 1-2 times the diffraction limit with the remainder in a spot 5-10 times larger. Harvesting 70-80% of energy outside of the central spot is essential for good efficiency. LASNEX calculations that used P. Gibbon's angle dependent absorption function showed a factor of 30 increase in focused intensity at the tip of a 5 degree cone compared to the incident intensity. Figure 3 shows the absorption fraction within 10 micron and 50 micron radii as a function of cone half angle for pointed cones as well as cones terminating in a slab of 10 micron radius. The heating experiments at ILE, Osaka used cones with half-angles of 15 and 30 degrees were well-matched to compressed cores with diameters from 30-50 microns.   However, the smaller spots needed for higher density compressions will need smaller angle cones. These calculations did not include hydrodynamic motion but indicate good performance of tight cones for focusing.

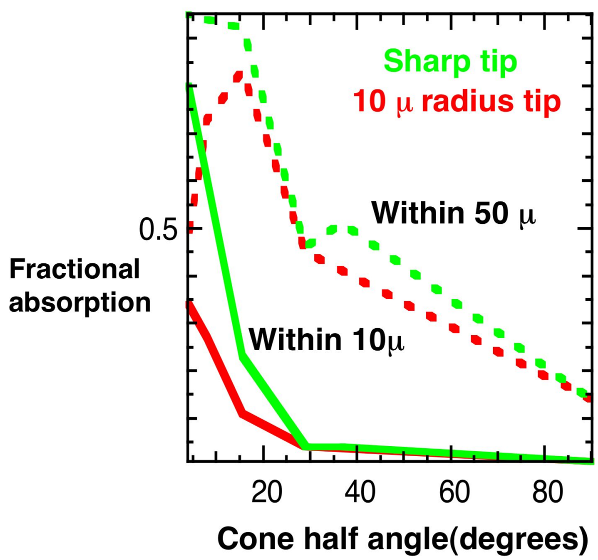

Figure 3: Absorption fraction versus cone half angle for cones terminating with a sharp and radiused tips.

Such extreme focusing is unlikely to occur in practice. A rippled reflecting surface will diffuse scattered light, moving it closer to the tip but not to the fine focus of specular reflection. The surface can become rippled due to ponderomotive and ablation pressure applied to the surface by the incident laser light. The rippling occurs more rapidly if the surface has been preheated so that the light interacts with a plasma of less than solid density. Recent experiments [Mac08] show that only 30% of laser light incident on a slab target with a 75 degree angle of incidence is specularly reflected with the rest apparently absorbed. At this time the evidence to support cone guiding of light is weak.

There have been claims [Sen04] coming from Particle-in-Cell (PIC) simulations that electrons will be channeled down the walls of the cone to the tip. There have even been experiments that support this contention. However, recent PIC simulations [Cot08b,Kemp08] indicate that the guided fraction of electrons is at best a small fraction of the total electrons produced and that the experimental evidence for escaping electron beams may be due to biases produced by the electric and magnetic fields around the corners of the target slabs. Therefore, we cannot rely on energy focusing to the cone tip much better than the focusing of the incident beam.

If there is prepulse, the result can be worse. Recent experiments [Bat08] found that the heating of a fluor at the end of cone with hot electrons produced by the laser equaled that of a directly illuminated slab only when there was no prepulse. A prepulse as small as 10 mJ produced a 100 micron long preplasma and decreased the coupling to the fluor by about an order of magnitude. PIC calculations suggested that the presence of the preplasma induced the generation of a magnetic field that drove the hot electrons into the the cone walls, not into the cone tip -- a result that directly contradicts Ref. [Sen04]. Other experiments at about the same prepulse level but more main pulse energy show better coupling, but we don't understand how allowed prepulse scales with main pulse energy. Clearly there is value in controlling the level of prepulse entering the cone.

2.1.2 Hydrodynamic design

The hydrodynamics of fast ignition target implosions has been the focus of a collaborative effort where experiments designed and interpreted at Lawrence Livermore National Lab (LLNL) under OFES target design funding, were fielded at the Omega laser at the University of Rochester with targets constructed at GA . This work has established a qualitative understanding of the trade-offs implicit in FI target design.

The first hydrodynamic design of an FI target using implosion around a cone was made using LASNEX [Hat00b]. This work has been extended to a sequence of FI designs at a variety of scales. Design predictions have been confirmed in experiments at the Omega laser at the University of Rochester as discussed below. By varying the drive symmetry, the assembled fuel's configuration can be changed from one with a low-density center to one with a more uniform density distribution.

A series of simulations and experiments designed to establish a detailed understanding of the compression of a reentrant cone fast ignition target has been carried out [Ste03, Ste04b, Sto04]. There were three major questions to address:

1. Do the hydrodynamics codes, which have been exhaustively tested on spherically symmetric targets, properly capture all of the physics in these extremely asymmetric cases.
2. Do shell-cone interactions interfere with efficient assembly of a dense core.
3. Does the design space allow simultaneous core assembly and ignition access?

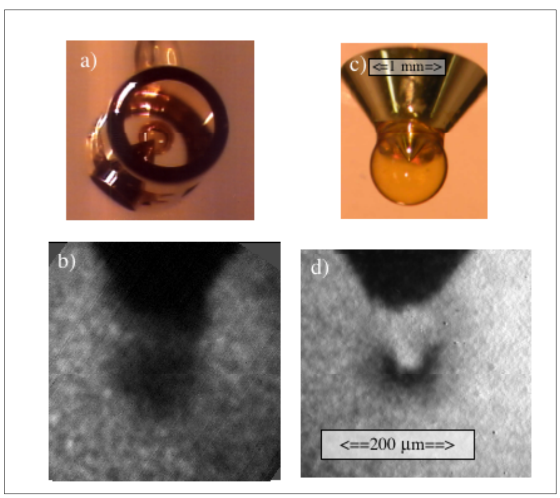

Figure 4: a) X-ray drive FI target and b) an x-ray back-lit image of the compressed core mixing with Au vaporized off the adjacent cone. c) Laser drive FI target and d) an x-ray back-lit image of the compressed core with no substantial core-cone mixing. The pairs of target and back-lit images are each shown.

The results showed reasonable efficiency in assembling a core but also two core-cone interactions that must be accounted for during optimization:

1. Laser-driven hohlraums cause substantial preheating of the reentrant cone, mixing Au vapor with the low-density core [Ste03] (Fig. 4 a,b). It should be noted that direct laser-driven targets exhibit substantially reduced cone preheat (Fig. 4 c,d), and is not thought to be a serious problem in that geometry [Sto04].
2. The cone tip is severely impacted by the hot gas exhausting from the core. This was suggested by simulations and experimentally confirmed by detailed measurements of the cone tip position during a collapse sequence (Fig.5) . The tip is pushed back by ~30 microns (more than its thickness) before fuel can be sufficiently assembled.

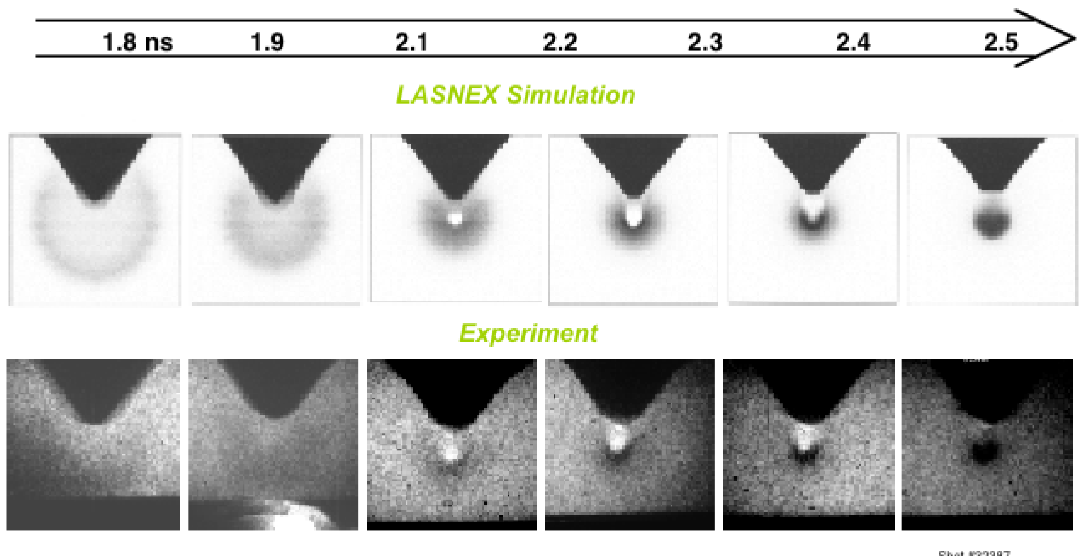

Figure 5: Framing camera pictures, simulated and experimental, of a cone target implosion. Taken with an Fe backlighter (6.7 keV, filtered with 13-mil Be to show self-emission at 2–4 keV).

We conclude that the hydrodynamic behavior of a FI target is qualitatively understood. Radiation transport and mixing are important processes in these targets and must be included for quantitative predictions. Further, it is clear from these results that the ignition path is sensitive to details of the hydrodynamic collapse; target performance can only be evaluated with an integrated model and tested with integrated experiments. Integrated modeling and testing is required to optimize FI target designs.

2.1.3 Code capabilities

Modeling the entire process of fast ignition involves physics that evolves on disparate temporal and spatial scales. Figure 6 summarizes the spatial and temporal scales over which these processes evolve. First, long pulse lasers (or x-rays) implode the mm scale capsule over an ~ns duration pulse. This is naturally simulated by radiation hydrodynamics. Next, the short-pulse high-intensity laser propagates through a sub-critical plasma depositing its energy into relativistic electrons at the critical surface. The characteristic spatial scale for this interaction is 100s of microns for the duration of the laser pulse (typically 10 ps). The short spatial and temporal scales together with the low density lends this portion of the problem to explicit collisionless PIC code modeling. The laser-generated electrons are then transported through 100s of microns of plasma towards the dense fuel core in 10s of ps. As noted above they transit through plasmas that range from low to high densities and that are generally cold. The need for explicit PIC code to resolve the Debye length and plasma frequency render conventional PIC modeling prohibitively expensive. Consequently, implicit hybrid PIC and Fokker-Planck codes in collision dominated regimes have emerged as the best technique to model this process. Finally, the electrons deposit their energy and initiate fusion burn - a job that can be performed by radiation hydrocodes.

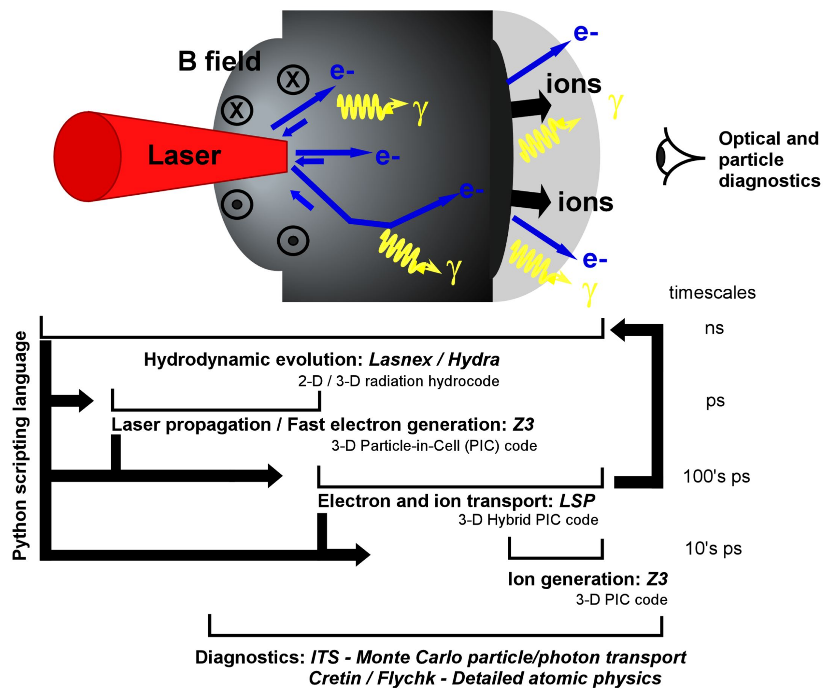

Figure 6: Code integration plan for short-pulse laser matter interactions.

LLNL has a full suite of computer codes designed to analyze high energy density physics that can be applied to the fast ignition problem. For hydrodynamic evolution, LLNL has developed LASNEX (2D) and HYDRA (2D,3D), both of which have many years of development and have been extensively tested against complex hydrodynamics and integrated hohlraum-capsule experiments. We anticipate that future FI designs may be intrinsically 3D in nature or may have 3D imperfections in either the implosion capsule or the radiation driving it. Therefore, 3D hydrodynamics codes that have burn, radiation transport and laser transport capabilities will be essential in modeling experiments in detail. HYDRA has these capabilities.

For electron (or proton) transport through the high-density plasma we use LSP [Wel01] This code has been developed by Mission Research Corporation and recently modified by us to run under the scripting language, PYTHON. LSP uses the direct implicit algorithm originally developed at LLNL during the 1980's [Fri-81,Hew-87]. Figure 7 [Tow05] shows the trajectories of electrons propagating through a slab of aluminum together with the self-consistent electric field, while Fig. 8 shows the measured rear surface temperature of the slab together with the LSP calculation. The calculated rear surface temperature distribution given a plausible hot electron input distribution agrees with the experimental measurements. Recent work has linked the output of Z3 into LSP for a first principles treatment. Early results show additional front surface heating as seen in experiments and indicate that this a promising approach for future development.

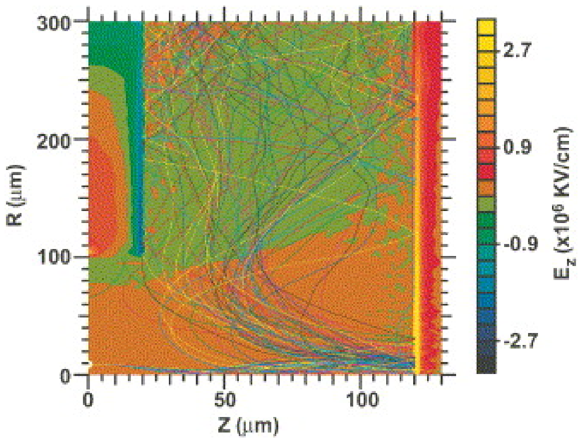

Figure 7: Trajectories of electrons initially injected at a radius of 10 microns
on top of color contours of the electric field component in the z-direction.

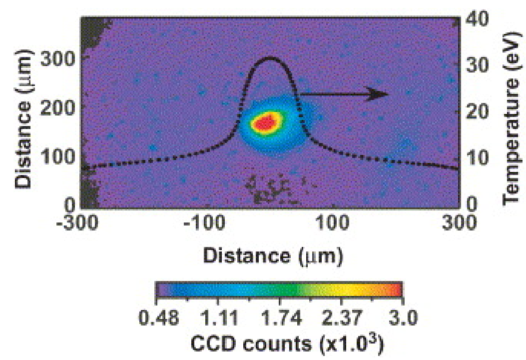

Figure 8: A contour plot of an XUV image of the rear surface of a 100 micron Al foil illuminated by the short-pulse Vulcan laser, overlaid by the rear-surface temperature profile predicted by the LSP code (dots).

Extensive simulation support is needed to develop reduced model insight with theory -- particularly for difficult saturation questions. For this purpose, we plan to employ the LLNL WARP code [Gro01]. This code was originally developed for electrostatic accelerator applications, but has been fully adapted for multi-species Vlasov plasma simulations in both 2D (5D x-p) and 3D (6D x-p) electromagnetic models due to symbiotic projects. WARP runs both in serial and parallel modes and is python interpreter based with extensive diagnostic capabilities developed for accelerator physics and this project in specific which will aid analysis of relativistic beam transport in plasmas. The code is being adapted to load a wide variety of relativistic distributions needed including those with finite geometry and incorporation of self-consistent space-charge effects. S.M. Lund has used WARP effectively for years and adequate time is freely available on a Linux-based parallel machine (12-node, 48 processor cluster "fusion") at LBNL for extensive runs. Ongoing synergistic projects have recently added a Manheimer type scattering model [Man97] and implicit modeling aspects [Fri81,Hew87] to the WARP which promise to further aid long-term usefulness of the code. Adaptive mesh refinement (AMR) capabilities of the EM field solvers in WARP can also be exploited to explore scale dependent effects in discretization choices made in simulations.

2.1.4 Integrated design

Designing targets for Fast Ignition (FI) requires an integrated set of computational tools together with the design expertise to use these tools effectively. Fast Ignition presents a coupled problem where fuel must be assembled efficiently into a compact mass and then energy must be coupled from a short pulse laser to the fuel mass that will then ignite and burn. The required tools include: 2D/3D radiation/hydrodynamics/ burn codes, radiation transport codes, laser-plasma transport codes, laser-plasma interaction codes and computer codes that can track particles through high-temperature, dense plasmas where the self-consistently determined electric and magnetic fields can significantly affect the transport. All of these classes of simulations must be linked together in order to obtain an accurate description of the physical phenomena. We have made significant progress in coupling the various codes. We have used the hot electron distribution calculated by Z3, our explicit PIC code, as a source in LSP, the implicit, hybrid PIC code used for transport modeling. Resulting preliminary calculations predict enhanced front-surface heating, in agreement with recent experimental measurements, as well as filaments carrying energy deep into the slab. Future work will include the effect of the plasma produced by the laser prepulse on the electron distribution function.

We have linked the output of one of our hydrodynamics codes, LASNEX, to LSP. The LASNEX calculation modeled a directly-driven, cone-focused implosion on the OMEGA laser at the University of Rochester. The background plasma used in the LSP calculation had the composition, temperature, and density of the imploded configuration produced in the LASNEX calculation as shown in Figure 9. Typical short-pulse lasers deliver 20-30% of their energy into spots a few times the diffraction limited spot-size with the remainder distributed in a much larger spot. For a 1 kJ laser this leads to approximately 300 joules available for heating. If this energy is incident in 10 ps (OMEGA EP spec) in a spot 10 microns in radius, then an incident intensity of 10^{19}W/cm^2 is obtained. Empirically, the coupling efficiency at this intensity is about 30%. An LSP calculation where 100 joules of electrons is injected into this system with average energy 1 MeV led to very little fuel heating—the resistive electric field and multiple scattering in the gold cone inhibited the transport. This illustrates the need to carefully design using integrated modeling tools to achieve reliable performance. It is anticipated that consistent design with these tools should mitigate problems found in these preliminary steps. The upcoming set of integrated experiments at Omega EP and NIF/ARC will be used to validate our integrated design capability.

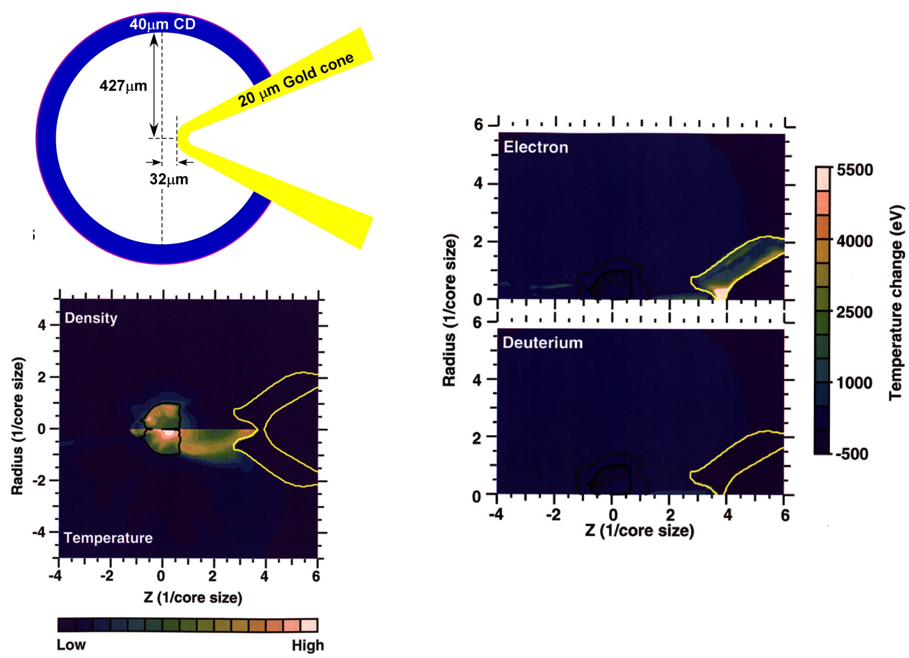

Figure 9: Imploded Omega cone focus target as calculated in LASNEX showing the temperature change in the target electrons and deuterium after the injection of hot electrons as calculated in LSP.

2.1.5 Electron beam-plasma instabilities

In fast ignition applications, intense, relativistic electron beams are transported in laboratory plasma to ignite a pre-compressed target with a dense core[Tab94,Atz99,Ros99]. The electron beam is formed in a short-pulse, high-intensity laser-plasma interaction in the tenuous coronal plasma (few times critical density) and propagates up a density gradient to deposit energy in the dense core. Cone targets [Tab97,Hat01,Kod02], which in recent years have dominated fast ignition target concepts, seek to minimize the beam transport distance within the plasma by moving the high-density core closer to the laser-plasma interaction region. However, even in the cone-targets, the beam must propagate through many plasma periods before stopping in the dense core while subject to a wide variety of plasma instabilities such as two-stream, Weibel, and filamentary modes [Bre04,Las99,Sil02,Yan93,Mil82,Car81,Mol75,]. These instabilities can inhibit transport of the beam into the dense core and/or modify stopping putting fast ignition design concepts in jeopardy. Advanced target designs proposed in the first part of this proposal seek to reduce the danger of such instabilities by minimizing beam propagation distance in the plasma. Nevertheless, it is desirable to more fully understand the range of plasma instabilities of consequence: both in terms of parameter ranges for target designs where they can be avoided and the consequence of strong instability growth in situations where they cannot be fully suppressed. Work outlined in this proposal will improve understanding of instabilities at issue in fast ignition applications. Such improved understanding will also benefit near-term high energy density laboratory plasma experiments, verification of codes employed in the support of near-term experiments and target design, and in astrophysics.

Detailed plasma simulations are used both to verify both fast ignition target design concepts and in support of ongoing high energy laboratory plasma experiments. Use of simulations as a tool in increasing understanding of experimental results is important because present experiments typically have limited diagnostics. Plasma instabilities, when present, are also often inadequately resolved yet still have implications in envisioned applications such as fast ignition. Moreover, large scale simulation verifications of fast ignition design concepts have often employed implicit particle advance methods [Fri81,Hew87] with timesteps larger than characteristic instability timescales making it unclear whether relevant instabilities can be properly modeled, or have purposely failed to resolve plasma instabilities in simulations with explicit particle advances due to the choice of timestep under the supposition that increased collisionality in denser core plasmas will render the instabilities irrelevant [Sen04]. This situation leads to inadequate confidence in the robustness of concepts developed with the aid of simulations that may not adequately reflect the consequences of plasma instabilities. Failure to properly resolve plasma instabilities in simulations can also hinder proper interpretation of results measured in present experiments due to limited diagnostics and reliance on simulations to aid interpretation of measurements. Given this situation, it is prudent to study relevant beam-plasma instabilities influencing beam transport in high energy density laboratory plasmas. Better understanding of instability characteristics can aid code benchmarking to increase confidence that important effects have not been neglected in both near-term experiment support and in fast-ignition target concept verifications. This is of critical importance due to the reliance placed on simulations.

Beam-plasma instabilities have been extensively studied using both analytic theory and simulations over many years. In spite of this large volume of work, extensions of are necessary to adequately clarify the situation for high energy density laboratory plasmas. Linear stability properties of beams in dense plasmas have been extensively studied using distributions of specific forms [Bre04,Mol75], and typically, collisionless Vlasov models of electrostatic two-stream, and electromagnetic Weibel/filamentary modes. Recent group work [Cot08a] extend this analysis to analyze effects resulting from initial distributions with proper relativistic form and weak collisional effects. Relativistic form Gaussian (Juttner) equilibrium distributions are found to have significantly different structure compared to nonrelativistic or weakly relativistic (Saddle-Point with with gamma-factor corrections) Gaussian form distributions commonly used to analyze instabilities. This is illustrated in Fig. 10 for equivalent distribution parameters with weakly and strongly (relevant to FI) relativistic parameters chosen for moment equivalent values of temperature T. Weakly relativistic cases (upper row) show projections different from Gaussian form (plotted in Saddle point form). Strongly relativistic cases (lower row) have radically different structure than the common Gaussian and other nonrelativistic form distributions often assumed. On overlay of an equivalent T Gaussian in this case would be off the scale of the plot. Preliminary analysis of beam distributions formed from the laser-plasma interaction at the critical density surface [Cot08a] indicate that the beam distribution has form similar to the Juttner distribution with strongly relativistic parameters.

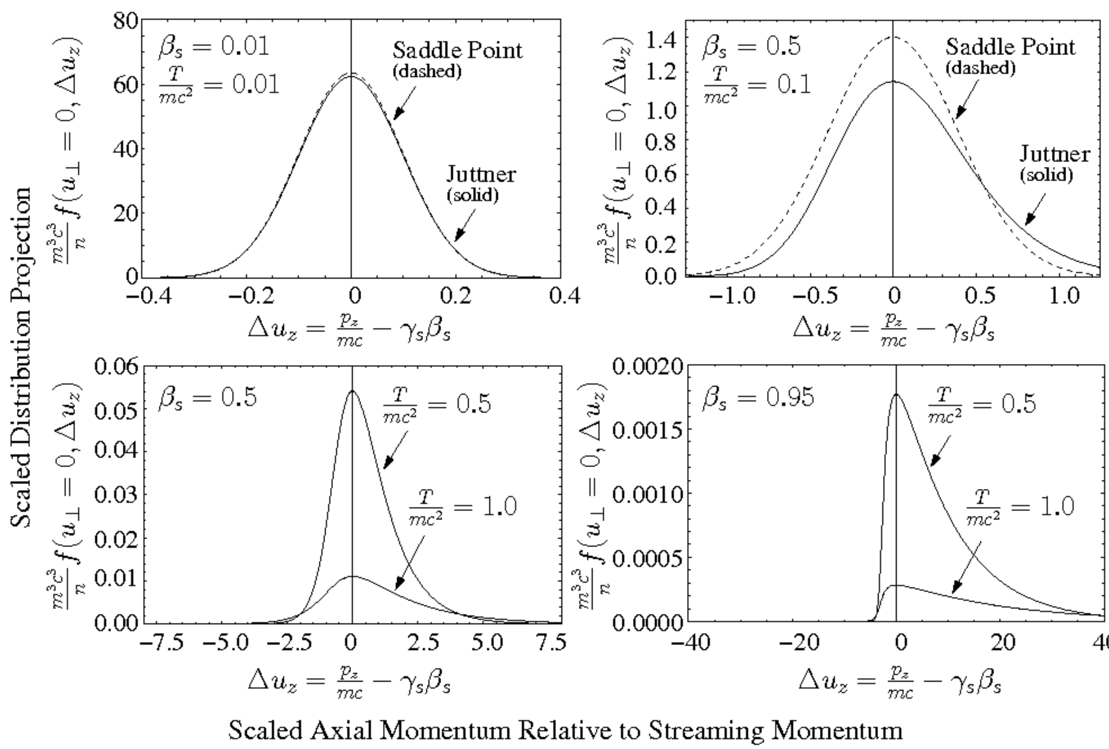

Figure 10: Relativistic form Juttner equilibrium distributions for weakly relativistic (upper row) and strongly relativistic (lower row) parameters. Strongly relativistic cases are show for several values of temperature T.

Recent studies [Cot08a] show that initial equilibrium beam distributions with proper relativistic form (with proper relativistic symmetry being more important than the specific form of the detailed distribution) resulted in significant reductions in linear mode growth rates for both 2-stream and Weibel/filamentary modes, but that contrary to what might be naively expected, collisions acting primarily on the cold plasma return current actually increase the parametric range of instability for Weibel/filamentary modes. An example of the strong reduction of mode growth rates due to relativistic distribution form is shown in Fig. 11. The most unstable mode for an initial relativistic waterbag distribution specifically chosen to be of analogous form to a relativistic Gaussian/Juttner distribution is found to have pronouncedly weaker linear growth for more strongly relativistic parameters characteristic of FI (lower row) relative to the weakly relativistic case (upper row). Extensions of this work are desirable to more fully quantify ranges of beam to plasma density (α) and collision frequencies that are potentially problematic and to explore implications of ion-acoustic and drift mode instabilities that have not been adequately addressed to date. Information on most unstable mode characteristics and parametric ranges is also extremely useful to allow benchmarking of the wide variety of codes presently employed to model high energy density laboratory plasmas.

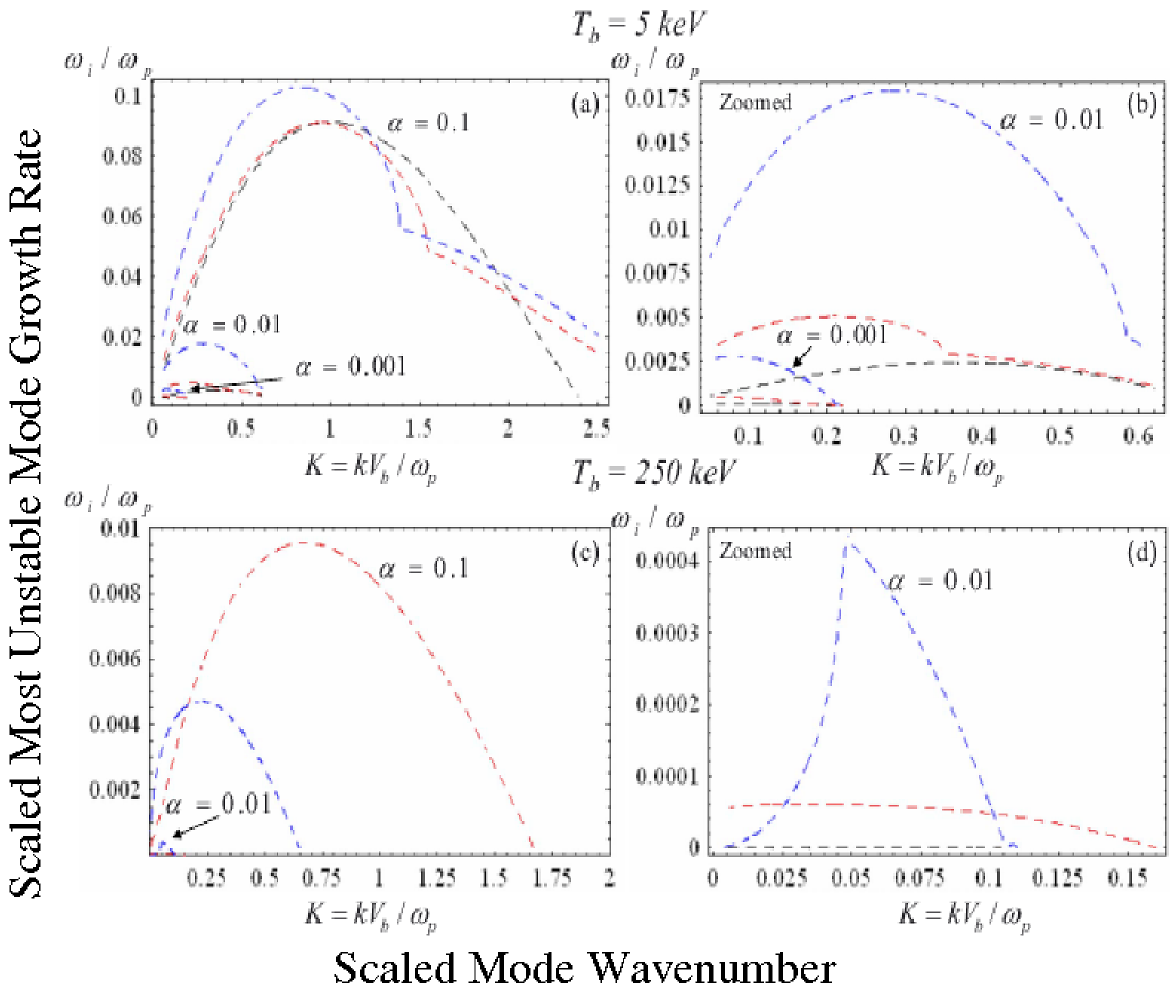

Figure 11: Maximum growth rate for filamentary instability versus mode wavenumber for a range of beam to plasma densities (labeled with α). The equilibrium distribution is a relativistic waterbag distribution.

Another aspect of the instability problem with less much work developed is on saturation effects of instabilities. Much is unclear on the levels of saturation anticipated and the implications of collisions and distribution structure (relativistic and otherwise) on the saturated state. This is an important issue since a relativistic beam transported in dense plasma supports a large range of plasma instabilities that typically have many plasma periods to evolve. Previous work using a Vlasov model suggests that Weibel/filamentary instabilities saturate as a level when the bounce frequency of particles trapped in the mode perturbations increases to a value comparable to the linear mode growth rate [Dav-72]. This prediction needs to be checked over the range of parameters of interest and the implications of collisions on the process and whether other considerations such as the defocusing effect of unscreened currents (Alfven type limits [Alf39]) may play a role in determining limiting states. Of particular interest is whether saturated Weibel/filamentary modes can be tolerated or if such modes will cause loss of subsequent directed energy transport into the dense core plasma in fast ignition applications. It is unclear whether filaments will coalesce up to the Alfven limit during saturated evolution while maintaining significant forward energy transport before being washed out by collisional effects or whether instabilities will cause an uncontrolled spray of filaments to be formed. The role of both the finite beam size and model dimensionality in such processes has also not been adequately quantified. Nonlinear stages of the development of filamentary instabilities can vary strongly due to the finite size transverse of the beam as well as the dimensionality of the filamentary structures and interactions used to model the 3D physical process in both analytical theory and in reduced simulations. Analysis of saturated states using reduced models based on moments or macro-particles might provide much needed parametric guidance on what can be tolerated.

2.2 Recent developments

2.2.1 Design of a test of electron coupling efficiency in the NIF

We are designing a full scale fuel assembly test of Fast Ignition electron coupling for the NIF using internal LLNL funds. We shall implode capsules (first CD then cryogenic DT) using radiation drive because the NIF beams are arranged for this and the beam smoothing required for direct illumination of the targets will not exist in the near term. Figure 11 shows gain curves [Tab06] for Fast Ignition when the capsule is indirectly imploded by lasers of various frequencies. We assume that the hot electron spectrum is given by ponderomotive scaling with a green laser. The curves are labeled by the compression laser frequency as well as the maximum energy that can be used in the ignition beam. These optima correspond to significantly lower implosion velocities with much higher fuel masses than hotspot ignition designs. Based on these optima we have developed symmetric (1D) and asymmetric (including a cone) designs that achieve high density (approximately 500-600g/cc in region where the column density accumulates. Figure 12 shows such a 1-D design. In addition we have developed designs based on self-similar solutions that do not have the central void typical in imploded capsules and instead feature a uniform density of the compressed fuel [Cla07]. Figure 13 illustrates the stagnated density distribution of a 2-D implosion including a cone. The issue of cone tip survival still exists, but this issue will be addressed in the internal LLNL program. We have addressed the issue of hard photon preheat of the cone with a four step mitigation program: coat the hohlraum wall with low-Z material to eliminate bound-bound transitions and reduce bound-free transitions; eliminate high-Z dopants from the outer part of the ablator where they might be a source of hard photons; put a layer of mid-Z filters near the fuel ablator interface; and tamp the cone with low-Z material to minimize both the motion of the high-Z cone material and the deleterious effects of any material that might be mixed with the fuel. These mitigation techniques have been tested in experiments at Omega. These past results together with ongoing work puts us in a good position to test new implosion concepts and ignition schemes.

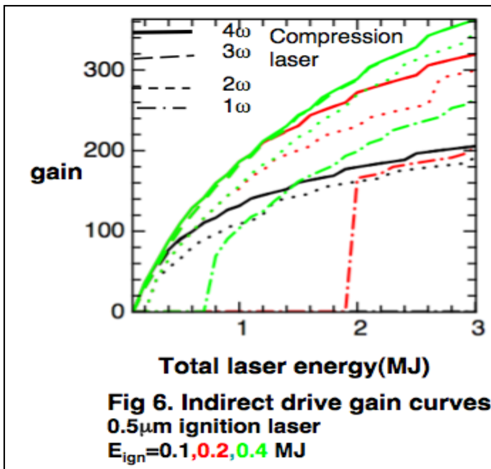

Figure 11:

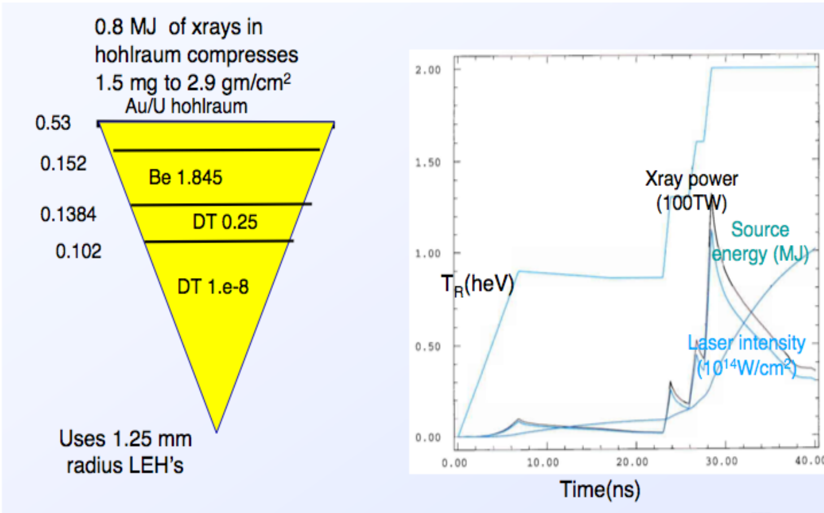

Figure 12: 1-D design for a Fast Ignition target.

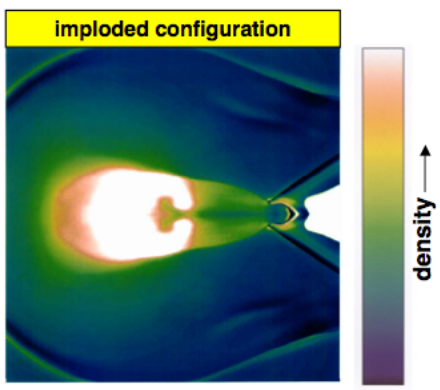

Figure 13: Stagnated density distribution of a 2-D implosion including a cone.

3 Proposed Research

3.1 Introduction

In collaboration with the and Fast Ignition Advanced Concept Exploration (ACE) program, the Fusion Science Center, the Livermore redirect of funding supporting the Sustain Spheromak Experiment (P. Patel, PI), and various internal Lawrence Livermore National Laboratory programs, this proposed effort will design high gain Fast Ignition targets as well as designs that can be tested on existing and upcoming facilities such as TITAN (LLNL), Omega EP (University of Rochester) and FIREX (Osaka University) and ultimately NIF (LLNL). We will make near term improvements to existing target concepts, develop new target concepts that will improve the long term prospects for Fast Ignition-fusion energy, and study beam-plasma transport instabilities so that we can optimize the properties of the background plasma through which the relativistic electrons produced by the short-pulse laser plasma interaction are transported.

Our project also leverages other programs that are developing capabilities needed for our success:

- LLNL's indirect-drive ICF research program (ID-ICF) leading to hotspot ignition on the NIF.
- LLNL's Strategic Initiative for Fast Ignition funding and LIFE program.

3.2 Target Design

1) Tamping the fusion fuel with a dense high atomic number material and/or supplying the ignition energy at the periphery of the ignition region instead of uniformly throughout the hotspot. For fuel that has been compressed to 300 g/cc, LASNEX calculations show that a combination of these techniques leads to 10 keV fuel temperatures and thermonuclear output equal to the injected energy for as little as one kilojoule of injected energy deposited in the fuel. Thermonuclear runaway, where the fuel temperature exceeds 20 keV and the yield exceeds 30 times the injected energy requires 4-5 kJ of injected energy. The corresponding energy requirements in the conventional central hot spot scheme where the target is DT with a column density of 1.5 gm/cm^2 and where the central ignitor region is heated are 5 and 15 kJ, respectively. We will design 1D implosions leading to this final state for both direct and indirect drive, estimate the amount of high-Z material mixed into the fuel, and then calculate 2D cone-shell implosions. Finally, we will transport electrons from the laser-plasma interaction point through the cone tip to the compressed fuel and self-consistently calculate the thermonuclear burn.

This outlined scheme may not be a good long term option for fusion energy production because too much energy will be used in compressing the tamper. However, it may be our best near-term hope to achieve significant burn via Fast Ignition. If we compress fuel to 300 g/cc, the ignition energy from Atzeni's fit [Atz99] is approximately 18 kJ delivered to the fuel. Using the 25% coupling efficiency inferred from the Osaka integrated experiments [Kod02], we need 72 kJ of laser energy delivered to the target. The NIF/ARC project where several NIF beams will be adapted to short pulse use promises to be the largest short pulse laser in the world for a decade. The retrofit should deliver about 10 kJ per quad (for 4 beams). Only about 6 kJ of this total 10 kJ energy per quad will focus to the cone tip. Because of architectural constraints, NIF can convert only 5 quads to short pulse use. Thus, without more laser infrastructure improvements, we should not plan on more than 30 kJ of laser light coupled to the cone tip. More efficient conversion of long pulse laser energy to short pulse energy is in principle possible. But space constraints in the NIF building preclude many possibilities that could apply in a new facility. Fuel configurations with DT tamped with high-Z may promise significant burn even for this reduced available laser energy. This computational effort will build on the capabilities developed in the LLNL Strategic Initiative to design targets for our coupling experiment.

2) Control laser prepulse by inserting absorbing micro- and nano-particles into the laser beam path that will absorb the prepulse, but still disassemble and disperse over the duration of the prepulse before the main pulse arrives. At this time we do not know the acceptable level of prepulse in cone-shell targets. There were experiments where 10 mJ was too much, but others where that level was acceptable. Optical Parametric Chirped Pulse Amplification (OPCPA) can reduce the prepulse energy by a factor of ~3e-5 relative to the main short-pulse energy. Hence a 10 kJ laser would have 300 mJ of prepulse. Even this level of prepulse may be unacceptable. Frequency doubling the laser can further reduce the prepulse to acceptable levels. However, this technique will reduce the energy delivered to the target and may increase damage to optical components. There are, in principle, other optical techniques that also can reduce prepulse substantially without the drawbacks of frequency doubling. The question is: can these techniques be deployed inexpensively and easily in an existing laser system not designed specifically for this mode of operation? The mechanical approach we seek to develop promises to be of little consequence to the existing laser architecture.

The challenge of the design is to absorb the unwanted light over a period of several nanoseconds and then to become transparent and without optical influence at the end of period when the main pulse is incident. This is reminiscent of saturable absorbers used in low power dye lasers. Such techniques have not yet been adopted for high energy petawatt lasers. The idea is to use an overdense plasma to absorb light efficiently and then to allow to the plasma to disassemble until it is several orders of magnitude underdense over a period of tens to hundreds of picoseconds. A characteristic velocity of a plasma with temperature ~1 eV is 10^6 cm/sec. In 100 picoseconds this object would expand one micron. Therefore, an object with initial scale of 0.1 microns would decrease in density by 3 orders of magnitude. We envision multiple layers of these objects so that the laser would burn through the entire ensemble over the full duration of the prepulse. The design work involves detailed model calculations of the response of micro- and nano-scale particles to laser light and a systems optimization to choose a distribution of particle sizes and locations in space.

3) Design of implosion systems for Fast Ignition where the capsule is directly illuminated from only two directions by laser beams. Most direct drive scenarios where capsules are imploded by laser light require uniform illumination of the capsule. This implies that the laser beams are uniformly distributed over 4π steradians. Achieving needed uniformity requires many beams, which has forced fusion chambers to use gas protection schemes or thin liquid walls. The use of gas protection schemes forces the reaction chamber to be of order 10 meters in radius and the solid first wall to be subject to neutron damage. Survival of materials subject to high neutron fluxes over a long time continues to be an area of continued research. There is no solution presently guaranteed for a lifetime first wall. Two-sided indirectly driven target illumination enables the use of thick liquid walls that have been a feature of reactors driven with heavy ion beams. In those reactor designs, the thick liquid walls simultaneously: protect the first solid walls from radiation damage, making them a lifetime component; breed tritium for future target fabrication; serve as an energy transfer medium to the heat engine that will make electricity; and provide an additional 14% energy gain due to exothermic neutron-lithium reactions. In addition, because the final optic must placed about 20 m away from the capsule in order to reduce its neutron damage, 4π illumination leads to final optics suspended in space with a very large (~50 m diameter) containment building around it. Such direct drive fusion chambers will be unlikely to result in attractive power plant architectures.

As part of our internal LLNL effort, we are designing targets that are indirectly driven with low incidence angle laser beams. Directly driven targets have approximately twice the gain of indirectly targets. Therefore, for fixed laser energy, a given electrical power output could be driven with half the repetition rate or a smaller energy laser driver could be used. Hence, there are clear advantages to two-sided direct illumination over uniform illumination.

There have been previous attempts at using low incident angle laser beams to directly illuminate fusion capsules. If we are attempting to implode spherical capsules with polar illumination, the light incident on the polar equator will refract away, coupling with low efficiency. Other capsule geometries may avoid this problem. In the so-called "Saturn target" [Cra05], a material ring is placed off the capsule equator to capture the refracted light and then heat the equatorial ablator via electron and radiation transport. Any geometry that provides substantially more than a glancing angle to the laser beam benefits from good absorption. Unfortunately, such geometries may not lead to adequately symmetric implosions for conventional central hotspot ignition. Because Fast Ignition requires less than half of the convergence ratio of hotspot ignition, it can tolerate larger pressure asymmetries than hotspot ignition. We will determine via hydrodynamic simulations which, if any, capsule geometry (including the Saturn geometry) can implode a target adequate for Fast Ignition.

4) Design of Fast Ignition capsules without an attached cone. The original Fast Ignition design [Tab91,Tab94] used high intensity laser beams (although below the ignition intensity) in order to bore a hole through the underdense plasma as well as the long shell between critical density and the ~10g/cc density surface. Recent massive-scale PIC simulations by Ren et al. [Ren08,Li08] show that laser-plasma instabilities in a mm long underdense plasma slow the hole boring progress and use substantial energy (comparable to the energy in the ignition laser) in order to reach the critical surface. Designs using a cone [Tab97,Hat01] produce more complicated implosions, pressure and density shadows, and significant standoff to protect the cone integrity. In addition, the prepulse of the peak intensity ignition laser can produce a plasma in the cone with a spatial extent of hundreds of microns. Another possibility is an asymmetric implosion where the initial capsule has a small radius of curvature at the end where the ignition laser will enter and a large radius of curvature where the bulk of the fusion mass is. Figure 14 [Tab94] shows the stagnated fuel mass of a small, compressed target capsule after hole boring. Note that the fuel mass away from the hole bored has the critical density surface at ~50 micron radius and the 0.1 critical density surface at ~150 microns. Here, the distance required for laser propagation through the underdense plasma is one tenth that of the case studied by Ren et al and the distance from the critical density to the high density fuel is less than 50 microns. Recent electron transport studies show that the hot electrons can efficiently propagate over this distance [Hon07]. Assembling a capsule with an attached cone causes additional complexity in fabrication that can be avoided in this technique. Using 2-D radiation-hydrodynamics codes, we will study stagnated states produced by a number of initial capsule builds with a variety drive asymmetries and asynchronies. This promises to provide valuable alternative designs to the cone target concepts presently dominating Fast Ignition studies.

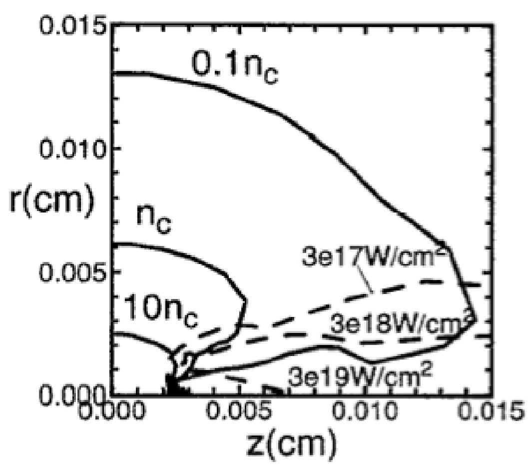

Figure 14: Density surfaces of a stagnated fuel mass after hole boring.

3.3 Electron beam-plasma instabilities and transport

Initial stages of the project will seek to:

- Extend earlier work [Cot-08a] to better define the range of parameters with instability issues when consistent relativistic distribution forms are applied and to explore whether ion-acoustic and/or drift-kinetic type instabilities may produce stronger insabilities relative to more studied, 2-stream and Weibel/filamentary modes.
- Apply developed WARP code capabilities to carry out parametric Vlasov simulations in 2D and 3D to quantify saturation and finite beam issues for initial beam distributions with correct relativistic symmetry such as Juttner [Cot-08a] and relativistic waterbag distributions [Cot-08a].
- Quantify parametric issues associated with the saturation of developed plasma instabilities

observed in Vlasov simulations including: role of finite beam geometry and Alfven' current limits (do filaments magnetically merge up to the Alfven' limit or are the distributions screened sufficiently where this is irrelevant), amplitudes and characteristics of saturated structures based on trapped particle interpretations, quantification of degradation of energy transport due to developed instabilities, and the role of dimension in the model (2D and 3D). Use improved code diagnostics to better explore saturated distribution structures.

- Provide code benchmark checks for implicit and other reduced model simulations to check validity of Vlasov limit and weak collisional model results.

Longer range goals are to:

- Develop sufficiently reduced theoretical models for saturated beams where a wide range of parameters can be efficiently explored in high energy density laboratory plasma applications. This will be attempted first within Vlasov model framework, and then incorporating collisional effects.
- Repeat parametric simulation studies made with correct symmetry relativistic distributions while including collisional effects to quantify the role of collisions in changing the unstable parameter range and saturated structures.
- Explore under what conditions increased collisionality might render developed plasma instabilities irrelevant as speculated in the literature [Sen04].

3.4 Proposed Program

FY09

Implosion design:

- Design 1-D implosions with high-Z tampers with multiple shock pulseshape as well as pulseshape leading to self-similar isochoric fuel configurations in direct and indirect drive.
- Reentrant cone design.
- Develop prepulse mitigation scheme.

Electron beam-plasma instabilities:

- Extend parametric studies of Vlasov beam-plasma instabilities using initial relativistic distributions and the WARP code to study: finite beam size effects, saturation characteristics, and beam collimation.
- Analyze possible parametric constraints due to acoustic and drift instabilities.

FY10

Implosion design:

- Produce integrated hydrodynamic design of capsule with high-Z tamper with cone
- Begin design of implosion without cone leading to short critical surface-high fuel density distance.
- Begin design of directly driven implosion driven from opposite poles.

Electron beam-plasma instabilities:

- Simulate the form of the relativistic beam distribution produced in laser-plasma interaction to determine optimal representations (relativistic Mawellian/Juttner or otherwise).
- Saturation effects in Weibel/Filamentary and other relevant instabilities within a Vlasov model.

FY11

Implosion design:

- Complete 2-D design implosion without cone leading to short fuel density distance to the critical surface.
- Complete design of directly driven implosion driven from opposite poles.

Electron beam-plasma instabilities:

- Evaluate collisional effects on relevant instabilities.
- Develop reduced moment or macro-particle model to characterize relevant instabilities.

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4. Textual Summary of Budget

The effort on this proposal can be divided into several research areas: optimal fuel assembly, prepulse mitigation, and electron transport. Proposal members, experience, and envisioned roles in this project are summarized as follows:

- M. Tabak (0.12 FTE) PI: Target design for fast ignition and IFE, plasma physics, LPI. Project guidance to maintain project relevance to design/experiment and applications. Optimal target assembly
- S. Lund (0.4 FTE): Beam-plasma instability modeling. Project theory and WARP code modeling/development.
- D. Ryutov (0.1FTE): Broad experience in the theory beam-plasma instabilities including extensive projects of relevance in the former Soviet Union. Project guidance on applicable theory and reduced model developments.
- S.C. Wilks (0.1FTE): LPI, connection with Patel laser-plasma interaction project, optimal fuel assembly and prepulse mitigation
- Postdoctoral researcher. To be trained in target design and other HEDP disciplines. Optimal fuel assembly, prepulse mitigation.

5. Management Plan

This is a small, single PI project. Proposal members have previous experience working together. A detailed management plan is not necessary.

6. Description of Facilities and Personnel

6.1 Facilities

Lawrence Livermore National Laboratory has several high capability and capacity supercomputer systems, including one of the world's most powerful, Blue Gene L. The current allotment for this research area is 4000 processor-hours/week. It is anticipated that this should be adequate for the proposal target design work.

Adequate computer time is also freely available to run the WARP code for relativistic beam transport simulations in plasmas. A Linux-based parallel machine (12-node, 48 processor cluster "fusion") at Lawrence Berkeley National Laboratory can be used for extensive runs. The WARP code also runs on personal computers under a wide variety of operating systems. Such computers can be adequate for 2D and smaller 3D simulations.

6.2 Personnel

Two-page biosketch CVs are provided for each participant in the proposal on the pages that follow.

6.2.1 Dr. Max Tabak

PRESENT POSITION:
AX-Division/Weapons and Complex Integration
Lawrence Livermore National Laboratory
Livermore, CA 94550
(925) 423-4791
Tabak1@llnl.gov

PERSONAL:
Citizenship: USA

PROFESSIONAL MEMBERSHIPS:
Fellow, American Physical Society

EDUCATION:

1975	Ph.D.	Physics	University of California, Berkeley
1970	B.S.	Physics	Massachusetts Institute of Technology

EMPLOYMENT:

1980-Present	Lawrence Livermore National Laboratory ICF Target Designer, Leader Applications Group in X- and AX-Divisions, Associate Program Leader in Fusion Energy Program
1977-1980	Carnegie-Mellon University, Postdoctoral Fellow
1975-1977	Weizmann Institute of Science: Postdoctoral Fellow
1970-1975	University of California, Berkeley: Teaching and Research Assistantships
1968-1970	MIT, Dept. of Earth and Planetary Sciences

HONORS:

Teller Medal, LLNL	2005
APS/DPP Excellence in Plasma Physics Award	2006

GENERAL RESEARCH INTERESTS:
Dr. Tabak received his S.B. from MIT and his Ph.D. from the University of California, Berkeley in experimental high energy physics . He followed this work with post-doctoral training in elementary particles at the Weizmann Institute of Science and at Carnegie Mellon University. Since 1980, Dr. Tabak has been associated with Lawrence Livermore National Laboratory and is now a Chief Scientist in the Defense and Nuclear Technology Department as well as Associate Program Leader for Inertial Fusion Target Design in the Fusion Energy Program there.
Dr. Tabak has broad experience in inertial fusion and has made seminal contributions in a number of areas including implosion hydrodynamics (adiabat shaping for stability control of directly driven capsules) , radiation transport and ICF target design. He was a member of the HALITE team that put to rest fundamental questions about the basic feasibility of achieving high gain in laboratory experiments. He led teams that designed the distributed radiator target for heavy ion fusion (versions are being considered for laser fusion) and the Z-pinch driven hohlraum target (the current baseline design at Sandia National Laboratory). He was the lead inventor of the Fast Ignition concept and has led the theoretical development of the idea since its inception. Early

theoretical work he led in the area of high intensity laser-plasma plasma interactions included prediction of ultra- large magnetic fields produced near the critical surface, production of electron-positron pair plasmas, channel formation, and efficient production of protons by ambipolar potentials in high intensity experiments. He also first suggested the cone-focus concept for Fast Ignition. In recognition of this work he received the Teller Medal of the American Nuclear Society in 2005. He is a Fellow of the American Physical Society. He was a co-recipient of the APS/DPP Excellence in Plasma Physics Award for his work on Fast Ignition.

RELEVANT PUBLICATIONS:

S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, "Absorption of Ultra-Intense Laser Pulses," *Phys. Rev. Lett.* **69**, 1383 (1992).

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P.E. Young, M.E. Foord, J.H. Hammer, S.C. Wilks, M. Tabak and W.L. Kruer, "Time Dependent Channel Formation in Laser-Produced Plasmas," *Phys. Rev. Lett.* **75**, 1082-1085 (1995).

E.P. Liang, S.C. Wilks, and M.Tabak, "Pair Production by Ultraintense Lasers," *Phys. Rev. Lett.* **81**, 4887 (1998).

M.Tabak, et al., "Direct Ignition of Fusion Targets with Ultra High Intensity Short Pulse Lasers," Lawrence Livermore National Laboratory patent disclosure IL8826B (1997).

R.P.J. Town, C.Chen, L.A. Cottrill, M.H. Key, W.L. Kruer, A.B. Langdon, B.F. Lasinski, R.A. Snavely, C.H. Still, M. Tabak, D.R. Welch, S.C. Wilks, "Simulations of Electron Transport for Fast Ignition using LSP," *Nuclear Inst. and Methods A* **544**, 61 (2005).

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M. Tabak, D.S. Clark, S.P. Hatchett, M.H. Key, B.F. Lasinski, R.A. Snavely, S.C. Wilks, R.P.J. Town, R. Stephens, E.M. Campbell, K.A. Tanaka, S. Atzeni, R. Freeman," Review of Progress in Fast Ignition," *Physics of Plasmas* **12**, 57305 (2005).

D.S. Clark and M. Tabak, "A Self-Similar Isochoric Implosion for Fast Ignition," *Nuclear Fusion* **47**, 147 (2007).

L.A. Cottrill, A.B. Langdon, B.F. Lasinski, S.M. Lund, K. Molvig, M. Tabak, R.P.J. Town, and E.A. Williams, "Kinetic and Collisional Effects on the Linear Evolutions of Fast Ignition Relevant Beam Instabilities," *Phys. Plasmas* **15**, 082108 (2008).

6.2.2 Dr. Steven M. Lund

PRESENT POSITION:
Physical Sciences Division, Heavy Ion Fusion Group
Lawrence Livermore National Laboratory, L-645
Livermore, CA 94550
(510) 486-6936
SMLund@llnl.gov

PERSONAL:
Citizenship: U.S.A

PROFESSIONAL MEMBERSHIPS:
American Physical Society

EDUCATION:

08/87-09/92	Ph.D.	Physics	*Massachusetts Institute of Technology*, Cambridge, MA (Nonneutral Plasmas, under Prof. R. C. Davidson)
08/84-06/87	B.S.	Physics	*Auburn University*, Auburn, AL

RESEARCH EXPERIENCE:

12/92-Present	Lawrence Livermore National Laboratory, Physicist (post-doc, term, Y-div and PhySci-div staff), Livermore, CA
09/92-12/92	Princeton Plasma Physics Laboratory, Princeton, NJ, Visiting Scientist
07/86-08/87	Leach Nuclear Science Center, Auburn, Al, Research Assistant
06/85-08/85	Ciba-Gigey Corp., McIntosh, AL, Electronics Technician

HONORS:
US Dept. of Energy Fellow in X-Division 93-94
President's award for top graduating senior in University (Auburn University 06/87)
Physics Dept. award for top graduating senior (Auburn University, 06/87)

GENERAL RESEARCH INTERESTS:
Theoretical and numerical studies of interactions between charged particles and electromagnetic fields, including the physics of: plasmas, charged particle accelerators and nonneutral plasmas, the generation of coherent electromagnetic radiation by relativistic electron beams, and mathematical physics. Analytic theory of linear/nonlinear collective waves and instabilities in beam/plasma systems, nonlinear dynamics, and charged particle beam optics. Transport of relativistic electron beams in plasmas. Development of and running computer simulations of beam/plasma systems using multidimensional particle-in-cell models and various physically motivated reduced models for experimental support, the study of and the identification of relevant processes in guiding analytic theory. Design of circular and linear accelerator systems including ion sources, beam transport lattices, RF and Induction based acceleration and bunch compression, and resonance suppression. Design of diagnostic instruments and other scientific apparatuses including novel electric and magnetic lenses for charged particle beam optics, accelerator beam diagnostics, and signal processing.

TEACHING EXPERIENCE:

US. Particle Accelerator School, J.J. Barnard and S.M. Lund, *Beam Physics with Intense Space-Charge*, Full Semester Class: 2008 (Annapolis, MD, U-Maryland), 2006 (Waltham, Mass, MIT), 2004 (Williamsburg, VA, William and Mary); Half-Semester Class: 2001 (Boulder, Co, U. of Colorado at Boulder)

SELECT PUBLICATIONS:

1. Steven M. Lund, Takashi Kikuchi, and Ronald C. Davidson, *Generation of initial Vlasov distributions for simulation of charged particle beams with high space-charge intensity*, Submitted for Publication, Physical Review Special Topics - Accelerators and Beams (2008).
2. Edward P. Startsev and Steven M. Lund, *Approximate analytical solutions for continuously focused beams and single-species plasmas in thermal equilibrium*, Physics of Plasmas **15**, 043101, 6 pages (2008).
3. Steven M. Lund, John J. Barnard, Boris Bukh, Sugreev R. Chawla, and Sven H. Chilton, *A core-particle model for periodically focused ion beams with intense space-charge*, Nuclear Instruments and Methods A **577** 173-185 (2007).
4. Ronald C. Davidson, Igor Kaganovich, Edward A. Startsev, Hong Qin, Mikhail Dorf, Adam Sefkow, Dale R. Welch, David V. Rose, and Steven M. Lund, *Multispecies Weibel instability for intense charged particle beam propagation through neutralizing background plasma*, Nuclear Instruments and Methods A **577**, 70-78 (2007).
5. Steven M. Lund and Sugreev R. Chawla, *Space-charge transport limits of ion beams in periodic quadrupole focusing channels,* Nuclear Instruments and Methods A **561**, 203-208 (2006).
6. Steven M. Lund, Sven H. Chilton, Edward P. Lee, *Efficient computation of matched solutions of the Kapchinskij-Vladimirskij envelope equations for periodic focusing lattices*, Physical Review Special Topics - Accelerators and Beams, **9**, 064201, 15 pages (2006).
7. S.M. Lund, D.P. Grote, and R.C. Davidson, *Simulations of Beam Emittance Growth from the Collective Relaxation of Space-Charge Nonuniformities*, Nuc. Instr. Meth. A **544,** 472-480 (2005).
8. Steven M. Lund and Boris Bukh, *Stability properties of the transverse envelope equations describing intense ion beam transport*, Physical Review Special Topics - Accelerators and Beams **7**, 024801, 47 pages (2004).
9. R.C. Davidson, H. Qin, and S.M. Lund, T*runcated Thermal Equilibrium Distribution for Intense Beam Propagation*, Phys. Rev. Special Topics – Accelerators and Beams **6,** 024402, 8 pages (2003).
10. S. M. Lund and J. J. Barnard and E. P. Lee and R. C. Davidson, “Beam Emittance Growth from the Collective Relaxation of Space-Charge Nonuniformities” UCRL-JC-148227-PT-1 (2002)
11. S.M. Lund and R. C. Davidson, *Warm-Fluid Description of Intense Beam Electrostatic Stability Properties*, Physics of Plasmas **5,** 3028-3053 (1998).
12. S.M. Lund, J.J. Barnard, G.D. Craig, A. Friedman, D.P. Grote, H.S. Hopkins, T.C. Sangster, W.M. Sharp, S. Eylon, T.J. Feseenden, E. Henestroza, S. Yu and I. Haber, *Numerical Simulation of Intense-Beam Experiments at LLNL and LBNL*, Nuc. Inst. Methods A **415,** 345-356 (1998).
13. R.C. Davidson, H.-W. Chan, C. Chen, S. Lund, *Equilibrium and Stability Properties of Intense Non-Neutral Electron Flow*, Rev. Mod. Phys. **63** 341-374 (1991).

6.2.3 Dr. Dimitri D. Ryutov

PRESENT POSITION:
Physicist, Fusion Energy Program
Lawrence Livermore National Laboratory, L-630
Livermore, CA 94551
(925) 422-9832
Ryutov1@llnl.gov

PERSONAL:
Citizenship: USA

PROFESSIONAL MEMBERSHIPS:
American Physical Society
American Association for the Advancement of Science
European Physical Society

EDUCATION:

10/62-09/65	PhD	Plasma Theory	Kurchatov Institute, Moscow, Russia
09/57-07/62	MS	Experimental Nuclear Physics	Moscow Institute of Physics and Technology, Moscow, Russia

PREVIOUS RESEARCH EXPERIENCE:

07/94-present	Senior Visiting Scientist; Physicist, FEP, Lawrence Livermore National Laboratory, Livermore, CA
07/68-09/97	Senior Scientist, Division Leader, Deputy Director, Chief Scientist, Budker Institute of Nuclear Physics, Novosibirsk, Russia (07/94-09/97 - on leave)
10/65-06/68	Junior Scientist, Kurchatov Institute, Moscow, Russia

HONORS AND AWARDS:
I.V. Kurchatov Fellowship (1960-62)
Graduated Summa Cum Laude (Moscow Inst. of Physics and Technology, 1962)
Corresponding Member, Academy of Sciences of Russia (1976)
Academician, Academy of Sciences of Russia (1992)
Fellow, American Physical Society (1998)
IOP Fellow (UK) (2003)
R&D100 Award (2004)
LLNL E. Teller Fellow (2007)

GENERAL RESEARCH INTERESTS:
Plasma physics and its applications; Environmental aspects of energy production; Space and astrophysical plasmas; X-ray optics; Advanced dynamics.

RELEVANT REFERENCES:

1. D.D. Ryutov, "Quasilinear relaxation of an electron beam in an inhomogeneous plasma," *Soviet Physics- JETP* **30**, 131 (1970).
2. B.N. Breizman, D.D. Ryutov, "Powerful relativistic electron beams in a plasma and in a vacuum (theory)," *Nuclear Fusion* **14**, 873 (1974)
3. A.A. Vedenov, D.D. Ryutov, "Quasilinear theory of streaming instabilities," *Reviews of Plasma Physics* **6**, 3 (M.A. Leontovich – Ed., Consultants Bureau, 1975).
4. D.D. Ryutov, G.V. Stupakov, "Formation of fast electron cloud during injection of intense relativistic electron beam into vacuum," *Sov. J. Plasma Phys.* **2**, 309 (1976).
5. K. Nishikawa, D.D. Ryutov, "Relaxation of relativistic electron beam in a plasma with random density inhomogeneities," *Journal of the Physical Society of Japan*, **41**, 1757 (1976).
6. D.D. Ryutov, "Critical vacuum current of a relativistic electron beam," *Soviet Physics-Technical Physics* **22**, 429 (1977).
7. B. Oliver, D.D. Ryutov, R. Sudan, "Charge and current neutralization in the formation of ion rings in a background plasma," *Physics of Plasmas*, **1**, 3383 (1994).
8. D.D. Ryutov, "Landau damping: half a century with the great discovery," *Plasma Phys. and Contr. Fusion* **41**, A1 (1999).
9. D.D. Ryutov, M.S. Derzon, M.K. Matzen, "The physics of fast Z pinches." *Rev. Mod. Phys.*, **72**, 167 (2000).
10. D.D. Ryutov, B.A. Remington, "Similarity laws for collisionless interaction of superstrong electromagnetic fields with a plasma", *Plasma Physics and Controlled Fusion*, **48,** L23-L31 (2006).

6.2.4 Dr. Scott C. Wilks

PRESENT POSITION:

AX-Division
Lawrence Livermore National Laboratory
Livermore, CA 94550
(925) 422-2974
Wilks1@llnl.gov

PERSONAL:
Citizenship: USA

PROFESSIONAL MEMBERSHIPS:
Fellow, American Physical Society

EDUCATION:

1989	Ph.D.	Physics	University of California, Los Angeles
1985	M.S.	Physics	University of California, Los Angeles
1983	B.A.	Physics	University of California, Berkeley

EMPLOYMENT:

1991-Present	Lawrence Livermore National Laboratory, Physicist in AX-Division
1989-1991	Lawrence Livermore National Laboratory, Postdoctoral Researcher
1983-1989	University of California at Los Angeles, Teaching Assistant and Researcher

HONORS:

2006	APS/DPP Excellence in Plasma Physics Award
2002	Defense Programs Award of Excellence for Contributions to the Stockpile Stewardship

GENERAL RESEARCH INTERESTS:
Dr. Wilks is an internationally recognized expert in modeling of ultraintense short-pulse laser interactions and fast ignition. His early work on applying Particle-In-Cell simulations to ultra-intense laser solid density plasma interactions led to several theoretical predictions about the interactions which were subsequently verified in experiment: namely, the ponderomotive scaling of hot electron temperatures, the presence of hundreds of megaGauss magnetic fields and hole boring of the laser pulse. This work played a key role in the early development of the fast ignitor concept. Recent work includes the development of a physical picture of ion acceleration, dubbed Target Normal Sheath Acceleration (TNSA). In 2002, he was awarded the Defense Programs Award of Excellence for his role in developing a novel hydrodynamics experimental campaign. He is a lifetime member of APS, and a co-winner of the 2006 American Physical Society "Award for Excellence in Plasma Physics Research" which was in recognition for contributions in developing the fast ignition inertial fusion concept.

RELEVANT PUBLICATIONS:

S.N. Chen, G. Gregori, P.K. Patel, H.-K. Chung, R.G. Evans, R.R. Freeman, E. Garcia Saiz, S.H. Glenzer, S.B. Hansen, F.Y. Khattak, J.A. King, A.J. Mackinnon, M.M. Notley, J.R. Pasley, D. Riley, R.B. Stephens, R.L. Weber, **S.C. Wilks**, and F.N. Beg, "Creation of Hot Dense Matter in Short-Pulse Laser-Plasma Interaction with Tamped Titanium Foils", *Physics of Plasmas* ***14***, 102701 (2007).

M. Allen, P.K. Patel, A. Mackinnon, D. Price, **S. Wilks**, and E. Morse "Direct Experimental Evidence of Back-Surface Ion Acceleration from Laser-Irradiated Foils", *Phys. Rev. Lett.* **93**, 265004 (2004)

S. C. Wilks, A. B. Langdon, M. Key, T. Cowan, D. Pennington, S. Hatchett, "Ion Acceleration Mechanisms in Ultra-Intense laser-Plasma Interactions", *Physics of Plasmas*, **8**, 542 (2001).

M. Roth, T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R.A. Snavely, **S. C. Wilks,** K. Yasuike, H. Ruhl, F. Pegoraro, S. V. Bulanov, E. M. Campbell, M. D. Perry, and H. Powell**,** "Fast Ignition by Intense Laser-Accelerated Proton Beams", *Phy. Rev. Lett.* **86**, 436 (2001).

MacGowan, A. MacKinnon, J. D. Moody, M. J. Moran, A. A. Offenberger, D. M. Pennington, M. D. Perry, T. J. Phillips, T. C. Sangster, M. S. Singh, M. A. Stoyer, M. Tabak, G. Thiebohl, M. Tsukamoto, K. B. Wharton, and **S. C. Wilks**, "Hot Electron Production and Heating by Hot electrons in Fast Ignitor Research", *Physics of Plasmas* **5**, 1966 (1998).

S.C. Wilks and W.L. Kruer, "Absorption of Ultra-Short Pulse, Ultra-Intense Laser Light by Solids and Overdense Plasmas", invited review article, *IEEE Journal of Quantum Electronics* **11**, 1954 (1997).

P.E. Young, G. Guethlein, **S.C. Wilks**, J. H. Hammer, W. L. Kruer, and K.G. Estabrook, "Fast Ion Production by Laser Filamentation in Laser-Produced Plasmas", *Phys. Rev. Lett.*, **76** 3128 (1996).

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6.3 Collaborators

The following is an alphabetized list of collaborators with proposal participants over the last 48 moths. This list includes collaborators or co-authors on research projects, books and book articles, reports, papers, abstracts, co-editors of scientific articles and compendiums and conferences proceedings, and students.

Abbate, S., LANL
Akli, K., GAT
Amendt, P., LLNL
Atchinson, R., LANL
Atzeni, S., U. Rome, Italy
Awe T., U. Nevada Reno
Barnard, J.B., LLNL
Barletta, B., MIT
Bartal, T., UCSD
Bauer, B., U. Nevada Reno
Beg, F. UCSD
Bettii, R., LLE
Bieniosek, F.M., LBNL
Bionta, R.M., LLNL
Briggs, D., SAIC Retired
Bukh, B., Princeton U.
Bulmer, R. LLNL
Buyko, A., Sarov, Russia
Callahan, D., LLNL
Campbell, E.M. Former GAT
Caporaso, G., LLNL
Casper, T.A., LLNL
Celata, C.M., LBNL
Chawla, S.R., U.C. San-Diego
Chen, H., LLNL
Chen, Sophia, UCSD
Chen, Yu-Juian, LLNL
Chernyshev, V.K., Sarov, Russia
Chilton, S.H., U.C. Berkeley
Chung, H.-K., LLNL
Clark, D., LLNL
Cohen, B.I., LLNL
Cohen, R.H., LLNL
Coleman, J., Lockheed-Martin
Cottrill, L., MIT/LLNL
Correll, D.L., LLNL
Counsell, G.F., Culham Science Center, UK
Cowan, T.E., U. Nevada Reno
Davidson, R.C., PPPL
Degnan, J., Kirtland Air Force Base
Dorf, L., LANL
Drake, P. U. Mich at Ann Arbor
Dumieres, E., U. Nevada at Reno
Efthimion, P.C., PPPL
Esaulov, A., U. Nevada Reno
Evans, R.G., Imperial College, UK
Fael, R., LANL
Foord, M., LLNL
Fowler, T.K., LLNL
Freemann, R.R., UCSD
Friedman, A., LLNL
Fuelling, S., U. Nevada Reno
Furno, I., Lausanne
Garcia Saiz, E., Belfast U., UK
Garanin, S., Sarov, Russia
Gilson, E.P., PPPL
Girsham, L., PPPL
Glenzer, S.H., LLNL
Goerz, D., LLNL
Goodrich, T., U. Nevada Reno
Gregory, G., Oxford U., UK
Grote, D.P., LLNL
Greenway, W., LBNL
Gregori, G., Oxford University
Guo, H., U. Washington at Seattle
Haber, I., U. Maryland
Hammer, J., LLNL
Hansen, S.B., LLNL
Hatchett, S., LLNL
Hau-Riege, S., LLNL
Helander, P., Culham Science Center, UK
Henestroza, E., LBNL
Herrmann, M., SNL
Hill, D.N., LLNL
Ho, D., LLNL
Hoffman, A., U. Washington at Seattle
Hofmann, I., GSI, Germany
Hooper, E.B., LLNL
Horioka, K., Tokyo Inst. Tech., Japan
Hudson, B. LLNL
Intrator, T.P., LANL
Ishida, A., Japan
Ivanovsky, A., Sarov, Russia
Jayakumar, R.J., LLNL
Kagonoivich, I.D., PPPL
Kane, J.O., LLNL
Kawata, S., Utsunomiya U., Japan
Kemp, A., LLNL
Key, M., LLNL
Khattak, F.Y., U. Belfast, UK

Kikuchi, T., Nagaoka U., Japan
King, J.A., UCSD
Kireeff Covo, M., LBNL
Kirkwood, R., LLNL
Kishek, R., U. Maryland
Klein, R.I., LLNL
Koniges, A., LLNL
Krzywinski, J., SLAC
Kwan, J.W., LBNL
LaBombard, B., MIT
Langdon, A.B., LLNL
Lapenta, L., LANL
Lasinski, B., LLNL
Lee, E.P., LBNL
Leitner, M., LBNL
LePape, S., LLNL
Li, Chikang., MIT
Liang, Edison, Rice University
Lidia, S.M., LBNL
Lindemuth, I., Retired
Link, T., Ohio State U.
LoDestro, L.L., LLNL
Logan, G.P., LBNL
London, R., LLNL
MacKinnon, A., LLNL
MacPhee, A., LLNL
Madziwa-Nussinov, T., LANL
Makhin, V., U. Nevada Reno
McCandless, B.C., LLNL
McKernan, M.A., LLNL
McLean, H.S., LLNL
Meier, W., LLNL
Meyerhofer D., U. of Rochcester
Michishita, Y., KEK, Japan
Miller, R., Retired
Mima, K., Osaka U., Japan
Mizuta, A., Max-Planck Inst., Garching, Germany
Mokhov, V., Sarov, Russia
Moller, J.M., LLNL
Molvig, K., MIT
Molvik, A., LLNL Retired
Moon, S.J., LLNL
Morse, E.C., UCB
Myatt, J., U. of Rochcester
Ni, P., LBNL
Notley, Rutherford Appelton Laboratory, UK
Olson, C., SNL Retired
Ortiz, J.C., LLNL
Park, H.-S., LLNL
Parks, P., GA
Pasley, J.R., UCSD
Patel, P.K., LLNL
Perkins, L.J., LLNL
Pearlsteinn, D., LLNL
Petrasso, R., MIT
Ping, Y., LLNL
Pound, M.W., U. Maryland College Park
Prager, S., PPPL
Qin, H., PPPL
Reginato, L., LBNL
Remington, B., LLNL
Reinovsky, R., LANL
Remington, B.A., LLNL
Riley, D., Belfast U., UK
Rognlien, T.D., LLNL
Romero-Talamas, C.A., LLNL
Roy, P.K, LBNL
Ruhl, H., U. Bochum, Germany
Scudder, D., LANL
Sefkow, A.B., PPPL
Seidl, P.A., LBNL
Sentoku, Y., U. Nevada at Reno
Sharp, W., LLNL
Sheehey, P., LANL
Shen, S., LLNL
Shepherd, R., LLNL
Siemon, R., U. Nevada Reno
Snyder, P.B., GAT
Sotnikov, V., U. Nevada Reno
Soufli, R., LLNL
Sovinec, C.R., U. Wisconsin at Madison
Startsev, E.P., PPPL
Steinhauer, L., U. Washington at Seattle
Stephens, R.B., GAT
Still, C.H., LLNL
Storm, E., LLNL
Sugimoto, H., Hiroshima U., Japan
Sun, X., LANL
Takabe, H., Osaka U., Japan
Takayama, K., KEK, Japan
Tanaka, K., Osaka U., Japan
Taylor, T., LANL
Terry, J.L., MIT
Thomas, C., LLNL
Thio, F., DOE
Town, R.P.J, LLNL
Trent, J.W., LLNL
Tsui, Y., U. Alberta
Umansky, M.V., LLNL
VanWoerkom, L., Ohio State U.
Vay, J.-L., LBNL
Verboncoeur, J., UCB
Waldron, W.L., LBNL
Weber, R.L, Ohio State U.
Wei, M.S., UCSD
Welch, D., Voss Scientific

Westenskow, G., LLNL Retired
Williams, E.A., LLNL
Wood, R.D., LLNL
Woodruff, S., Woodruff Scientific
Wootton, C.J., UCB
Wurtele, J., UCB
Xu, X.Q., LLNL
Yakubov, V., Sarov, Russia
Yu, S.S., LBNL
Zhang, B., LLNL
Zweben, S., PPPL

Abbreviations:

GAT	General Atomics
GSI	GSI, Darmstadt, Germany
KEK	Society of High Energy Research, Tskuba, Japan
LANL	Los Alamos National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LLE	Laboratory of Laser Energetics, Rochester
LLNL	Lawrence Livermore National Laboratory
MIT	Massachusetts Institute of Technology
PPPL	Princeton Plasma Physics Laboratory
SAIC	Science Applications International Corporation
SLAC	Stanford Linear Accelerator Center
SNL	Sandia National Laboratory
UCB	University of California at Berkeley
UCSD	University of California at San-Diego
UK	United Kingdom

7. Other Current and Pending Support

Other support for proposal members contingent on the funding of this proposal is listed below:

Max Tabak:
Contingent on funding of this proposal:
50% LDRD, Strategic Initiative, Fast Ignition
38% Teller Fellowship

Steven Lund:
Contingent on funding of this proposal:
60% OFES program to develop heavy ion drivers for high energy density physics

Dmitri Ryutov:
Present support: (Effort will be adjusted contingent of funding of this and other proposals)
58.5% Teller Fellowship
16% Magnetized Target Fusion Research, DOE Program
8.5% Office of Fusion Energy Science Programs
8.5% LLNL Exploratory Research LDRD, Innovative Divertor
8.5% Linac Coherent Light Source, SLAC, X-Ray Optics and Diagnostics
Pending proposals:
10% "Advanced Target Design for fast Ignition", Co-Investigator, HEDLP Proposal
8.5% "Concept Assessment for In Situ Measurements of Thermal Conductivity of Warm Dense matter," PI, HEDLP proposal
5.5% "Eagle Nebula: The Dynamics of Radiatively Driven Molecular Clouds in the Sky," Co-Investigator, HEDLP Proposal

Scott Wilks:
Present funding: (Effort will be adjusted contingent on funding of this proposal)
40% OFES Short Pulse Experiment/Code Development
30% LIFE (Laser Inertial Fusion Fission Engine) Project
10% LDRD, Labwide, Electron-Positron Jet
10% Magnetron Simulation effort for NIF
10% LDRD, Ultra-intense Laser and Reduced Mass Target

7B Relation to other programs

The program outlined in this proposal has several connections with other programs sponsored by the DOE's Office of Science, and by NNSA. The proposed program draws strength and leverage from these other programs, but it is essentially independent of their missions and goals.

7B.1 NNSA

There is no currently funded NNSA program that explicitly supports Fast Ignition, although all of the original Fast Ignition concepts and experiments were funded by NNSA or its predecessor in the DOE Defense Programs. Recently, there has been renewed interest in Fast Ignition by NNSA. Omega EP is funded by NNSA. In further programmatic support for Fast Ignition by NNSA is uncertain at this time.

7B.2 Advanced Concept Exploration Program in Fast Ignition Physics

This project designs, performs, and analyzes short pulse laser experiments in support of Fast Ignition point designs.

7.B.3 Fast Ignition Strategic Initiative at LLNL

LLNL has an internally funded (LDRD) Strategic Initiative to design and field radiation-driven, full-scale Fast Ignition fuel assemblies that will then be irradiated with 8 kJ of short pulse laser energy as an electron transport coupling test. If this experiment is successful, it may be a precursor to a full scale ignition and high gain attempt.

7.B.4 Fusion Science Center for Fast Ignition and High Energy Density Physics

This effort supplies funding for a number of university-based projects in Fast Ignition and High Energy Density Physics. We share information with this center and have been co-authors on some of their publications. The PI of this proposal is an advisor to the Fusion Science Center (FSC).

7.B.5 University Collaboration

We anticipate collaborations with researchers at universities. The researchers listed below have expressed interest in directly participating in aspects of the proposal and/or in providing graduate student support and supervision in support of the project. These university contacts promise to leverage the resources and further develop important contacts and cooperation between Lawrence Livermore National Laboratory (LBNL) and universities that will be beneficial to the DOE supported research. Both Profs. John Verboncoeur and Jonathan Wurtele are located at UC Berkeley making direct collaborations straightforward. A proposal participant (S.M. Lund) has a joint appointment at LLNL and LBNL and has worked effectively with Profs. Verboncoeur and Wurtele, including joint supervision of a graduate student (S.H. Chilton, Masters, UC Berkeley Nuclear Engineering Department).

- Edison Liang
  Professor, Rice University
  Role: Beam transport in plasmas.
- John Verboncoeur
  Professor, Nuclear Engineering Department, University of California at Berkeley
  Role: General student recruitment and supervision, simulation of beam transport in plasmas including relativistic scattering effects.
- Johnathan Wurtele
  Professor, Physics Department, University of California at Berkeley
  Scientist, Lawrence Berkeley National Laboratory
  Role: General student recruitment and supervision, general plasma and beam transport theory, and High Energy Density Physics.

Appendix: Letters of Endorsement

Letters of endorsement are included on the following pages.

UNIVERSITY OF CALIFORNIA, SAN DIEGO UCSD

BERKELEY • DAVIS • IRVINE • LOS ANGELES • MERCED • RIVERSIDE • SAN DIEGO • SAN FRANCISCO SANTA BARBARA • SANTA CRUZ

Dr. FARHAT BEG, DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING (MAE),
9500 GILMAN DRIVE, LA JOLLA, CALIFORNIA 92093-0411, (858) 822-1266, (858) 534-4543 FAX, Email: *fbeg@ucsd.edu*

September 11, 2008

TO WHOM IT MAY CONCERN

Dear Sir or Madam:

I am writing this letter to strongly support proposal entitled " Advanced Target Design for Fast Ignition" by Dr. Max Tabak and colleagues. The proposal addresses key and fundamental issues relevant to fast ignition. Particularly, it addresses the issue of preplasma created by the inherent prepulse in cones in integrated fast ignition experiments, which is crucial for delivering hot electron energy to the hot spot in the compressed fuel. In addition, proposal facilitates study of electron plasma instabilities analytically and numerically using 3D PIC codes, which will provide information about the enhanced stopping and scattering of the beam in the fuel.

In conclusion, both fast ignition and High Energy Density Science will greatly benefit with the proposed work. Therefore, I strongly support the proposed work on Advanced Target Design for Fast Ignition.

Sincerely yours,

Farhat Beg

Farhat Beg
Associate Professor of Engineering Physics

NIF Programs Directorate, L-470
P.O. Box 808 7000 East Avenue
Livermore, CA 94550

Sept 11, 2008

To whom it may concern

Advanced target design for fast ignition

I am writing in support of the proposal by Max Tabak and his colleagues.

Fast ignition has enormous potential and is the subject of intense investigation worldwide but it also has significant physics issues that are unresolved and a need to advance beyond the initial concepts to optimize its exploitation.

They key to realizing the potential of fast ignition is design studies to guide future experiments.

This proposal draws together internationally recognized and outstanding experts in such design and is backed by their access to leading numerical modeling capabilities developed in the national ICF program.

The essence of the proposal is to explore advanced design options that could improve both the near and long term prospects for fast ignition, that are not part of current programs. The concept of fast ignition itself is due to advanced design studies conducted more than a decade ago by some members of this team and this attests to their capabilities.

I believe this is work that could have a very significant impact on the future of fast ignition and that it strongly merits support.

Yours sincerely,

Michael H. Key
Senior Scientific Advisor, Petawatt Science
NIF Programs Directorate
Lawrence Livermore National Laboratory

11 Sept. '08

Dr. M. Tabak
P.O. Box 808
Livermore CA 94551

Re: Advanced Target Design for Fast Ignition

Dear Max:

The fast ignition (FI) concept you developed promises higher gain, relaxed driver requirements, and lower ignition threshold than the central hot-spot approach, making it currently the most attractive route to a burning plasma and for development of inertial fusion energy (IFE).

The ignition part of the concept has proved difficult. The current baseline approach to FI uses a reentrant cone to, as we initially thought, simply to provide a clear path to the core. As the experiments of our group have shown, generating the hot electrons at the laser-plasma-interface (LPI) inside the cone, and getting them out and into the dense core is a complex affair, and the cone is never simply an empty shape. It is partially filled on the inside with blowoff from the ignitor laser prepulse, has a shock traveling through its walls, and is shedding material into the imploding shell.

One has to think of the cone as having multiple roles: 1) controlling the environment in which the laser propagates and the electrons are generated so that the electrons propagate in a forward direction with the appropriate energy spectrum, 2) allowing them passage through the cone wall into the plasma with minimal energy loss and scattering, 3) maintaining those properties in the face of the forces and radiation resulting from the shell implosion just outside the cone, and 4) minimizing cone-caused degradation of the implosion. These requirements are to some degree at odds with one another, and put stringent performance specifications on the ignitor laser as to pointing accuracy and allowable prepulse. Moreover, the cone interacts with the shell during the implosion, to the detriment of both.

Clearly the ignition process needs detailed attention. The OFES funded project on Advanced Concept Exploration of Fast Ignition, of which I am a part, is studying the physics of the ignition process, both experimentally and through modeling, and developing the resulting specifications necessary to make a reentrant cone work. It would be extremely helpful in this effort to have a group led by you using the developing understanding, to consider what the best laser-plasma interface should be – whether a simple reentrant cone or some more sophisticated structure, or …

The interchange of performance/physics data on our part with interface ideas backed up by modeling on yours would considerably improve the efficiency with which we approach an optimum solution. Best of success with your proposal.

Sincerely,

Richard Stephens
P.I. Fast Ignition Advanced Concept Exploration Program

Chief Scientist, Inertial Fusion
General Atomics

3550 GENERAL ATOMICS COURT, SAN DIEGO, CA 92121-1122 PO BOX 85608, SAN DIEGO, CA 92186-5608 (858) 455-3000